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DEVELOPMENT OF A REAL-TIME DIGITAL TRAIN DYNAMICS SIMULATION COMPUTER PROGRAM

by

K.J. Rod Mathewson

DSL Dynamic Sciences Limited

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91-02514/

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LANGUAGE NOTICE

Un sommaire en français de ce rapport est inclus avant la Table des matières.

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Acknowledgments

The project team wants to acknowledge the support and suggestions of Mr. Philip Hamill of the National Research Council of Canada (NRC) and of members of his staff.

Transport Canada / Transports Canada

PUBLICATION DATA FORM

1. Transport Canada Publication No.	2. Project No.	3. Recipient's Catalogue No.
TP 10427E	6745	

4. Title and Subtitle	5. Publication Date
DEVELOPMENT OF A REAL-TIME DIGITAL TRAIN DYNAMICS SIMULATION COMPUTER PROGRAM	May 1990
	6. Performing Organization Document No. NRS222-00-UM1
7. Author(s) K.J. Rod Mathewson	8. Transport Canada File No. D1465-108-12
9. Performing Organization Name and Address DSL Dynamic Sciences Ltd. 350 Ste. Croix Blvd. St. Laurent, Quebec H4N 2L3	10. DSS File No. 11SD.T8200-2-2549
	11. DSS or Transport Canada Contract No. OSD82-00179
12. Sponsoring Agency Name and Address Transportation Development Centre (TDC) 200 René Lévesque Blvd. West Suite 601, West Tower Montreal, Quebec H2Z 1X4	13. Type of Publication and Period Covered Final:Apr '83-Dec '89
	14. Project Officer D.W. Dibble

15. Supplementary Notes (Funding programs, titles of related publications, etc.)

16. Abstract

As part of the broader objective of providing the railways, and others, with a real-time research and simulation capability for longitudinal train action and control, the project objectives were:

- to develop a real-time simulation program for longitudinal train dynamics and control which provides the ability for the operator to determine dynamic longitudinal forces at couplers and the longitudinal accelerations of cars within the train.
- to set up the model on facilities at the National Research Council of Canada (NRC) so that special research studies may be conducted.

These objectives have been met.

A full simulator has been implemented at NRC and is currently available for use. NRC also has a complete and detailed documentation package covering all aspects of use of the simulator.

This final report provides an overview of the project and the functional characteristics of the simulator. Models, outputs, and the preparation of inputs are discussed in sufficient detail for potential users to determine whether the simulator can be applied to their situation.

It is recommended that better field data be acquired so as to strengthen the validation.

17. Key Words	18. Distribution Statement
Train simulator, longitudinal train dynamics, train action	Limited number of copies available from the Transportation Development Centre.

19. Security Classification (of this publication)	20. Security Classification (of this page)	21. Declassification (date)	22. No. of Pages	23. Price
Unclassified	Unclassified	---	66	--

TDC/CDT 79-005 Rev 88

Canada

Transports Canada Transport Canada

FORMULE DE DONNÉES POUR PUBLICATION

1. N° de la publication de Transports Canada	2. N° de l'étude	3. N° de catalogue du destinataire
TP 10427E	6745	

4. Titre et sous-titre	5. Date de la publication
DEVELOPMENT OF A REAL-TIME DIGITAL TRAIN DYNAMICS SIMULATION COMPUTER PROGRAM	Mai 1990
	6. N° du document de l'organisme exécutant: NRS222-00-UM1

7. Auteur(s)	8. N° de dossier — Transports Canada
K.J. Rod Mathewson	D1465-108-12

9. Nom et adresse de l'organisme exécutant	10. N° de dossier — ASC
DSL Dynamic Sciences Ltée 350, boul. Ste. Croix St. Laurent (Québec) H4N 2L3	11SD.T8200-2-2549
	11. N° de contrat — ASC ou Transports Canada: OSD82-00179

12. Nom et adresse de l'organisme parrain	13. Genre de publication et période visée
Centre de développement des transports (CDT) 200 ouest, boul. René-Lévesque Tour ouest, suite 601 Montréal (Québec) H2Z 1X4	Final:avr '83-déc '89
	14. Agent de projet: D.W. Dibble

15. Remarques additionnelles (Programmes de financement, titres de publications connexes, etc.)

16. Résumé

Dans le cadre du programme visant à fournir aux sociétés ferroviaires et à d'autres utilisateurs potentiels un outil de recherche par voie de simulation fonctionnant en temps réel sur la dynamique des trains, la présente recherche avait les objectifs suivants :

- élaborer un programme fonctionnant en temps réel et permettant de simuler la dynamique des trains et, de ce fait, de mesurer l'amplitude des forces longitudinales s'exerçant sur les attelages et celle des accélérations agissant sur les wagons.
- mettre ce programme en oeuvre au Conseil national de recherches du Canada (CNRC) en vue de lancer les recherches correspondantes.

Ces objectifs ont été atteints.

Un programme complet de simulation existe maintenant au CNRC, prêt à être utilisé, ainsi qu'une documentation exhaustive et détaillée complète.

Le présent rapport final rend compte de cette recherche et explicite les caractéristiques du programme de simulation. Modèles, sorties et paramétrisation préalable y sont expliqués avec assez de détails pour permettre aux intéressés de se rendre compte si ce programme est bien celui qu'il leur faut.

Enfin, le rapport préconise l'acquisition de données vérifiées afin de pouvoir valider le programme.

17. Mots clés	18. Diffusion
Simulateur de conduite de trains, forces longitudinales, comportement des trains.	Le Centre de développements des transports dispose d'un nombre limité d'exemplaires.

19. Classification de sécurité (de cette publication)	20. Classification de sécurité (de cette page)	21. Déclassification (date)	22. Nombre de pages	23. Prix
Non classifié	Non classifiée	---	66	--

Summary

As part of the broader objective of providing the railways, and other potential users, with a real-time research and simulation capability for longitudinal train action and control, the project objectives were:

- to develop a real-time simulation program for longitudinal train dynamics and control which provides the ability for the operator to determine dynamic longitudinal forces at couplers and the longitudinal accelerations of cars within the train.

- to set up the model on facilities at the National Research Council of Canada ("NRC") so that special research studies may be conducted.

The scope of the project included:

- definition of functional requirements for the simulator, especially as regards modelling and the level of detail of the required input data;

- definition of user methodology, in terms of both off-line preparation of input data and user interaction during a simulation session;

- development of an acceptance test procedure by which NRC and TDC would be able to ensure that the product meets the defined requirements;

- design and development of the software at DSL in Montreal;

- implementation and acceptance testing of the system at NRC in Ottawa;

- demonstration of the use and capabilities of the system using case studies;

- preparation of a summary report highlighting the procedures and important results of these case studies;

- provision, to NRC and to TDC, of the complete software package including software and documentation consisting of complete operating manuals, technical description of the models, and a summary of the system's capabilities, potential applications, and basic data requirements.

A project steering committee, composed of representatives of NRC, TDC, and the railway industry, were an important asset in establishing appropriate requirements for the system. They also contributed through attending, and commenting on, the demonstration and on the system capabilities document.

The final product exceeded original expectations due, in large part, to a pause in the project during which DSL was able to significantly enhance the simulator as a result of developing a commercial training simulator. Many of the elements developed for the latter have been implemented in the final system.

NRC personnel participated closely in the project, particularly in defining, executing, and reporting on, the case studies. The resultant report is included as Appendix B to this final report.

All project objectives have been met or exceeded.

A full simulator has been implemented at NRC and is currently available for use. NRC also has a complete and detailed documentation package covering all aspects of use of the simulator.

This final report provides an overview of the project and the functionality of the simulator. Models, outputs, and the preparation of inputs are discussed in sufficient detail for a potential user to determine whether the simulator can be applied to his case.

Although thorough validation is frustrated by a lack of recent credible data against which to compare the results of simulation, the simulator may be used profitably for investigations into the dynamic longitudinal behavior of trains.

The ease of use of the simulator will attract users; as evidence, it has already been used by the Quebec North Shore and Labrador Railway.

If, for some special application, modifications or enhancements are required, those at NRC have sufficient documentation and experience to implement the changes. Wherever they were foreseeable, the software has been designed to permit such additions to be implemented easily.

In the event that NRC is unable to effect a particular modification, DSL is available to support them as required.

The acquisition of current valid test data against which the models can be better validated would be welcome. This would enhance the credibility of simulation results, an important aspect if, for example, such results are to be used as formal evidence in a legal or paralegal context. Such test data should, ideally, cover modern equipment and long trains.

The additions of a control stand would render the simulator more realistic. If railway operating personnel are to control the simulated trains, this would be a definite asset.

Sommaire

Dans le cadre du programme visant à fournir aux sociétés ferroviaires et à d'autres utilisateurs potentiels un outil de recherche par voie de simulation fonctionnant en temps réel sur la dynamique des trains, la présente recherche avait les objectifs suivants:

- élaborer un logiciel fonctionnant en temps réel et permettant de simuler la dynamique des trains et, de ce fait, de mesurer l'amplitude des forces longitudinales s'exerçant sur les attelages et celle des accélérations agissant sur les wagons.

- mettre ce logiciel en oeuvre au Conseil national de recherches du Canada (CNRC) en vue de lancer les recherches correspondantes.

La recherche avait la portée suivante:

- définition des fonctionnalités du logiciel de simulation, notamment pour ce qui est de la mise en équation des données d'entrée et de leur niveau de détail;

- définition de la méthodologie d'utilisation: paramétrisation préalable des données d'entrée et interaction homme-machine durant les simulations;

- élaboration d'une procédure d'acceptation permettant au CNRC et au CDT de vérifier que le produit final satisfait aux exigences définies;

- élaboration et mise au point du logiciel chez DSL à Montréal;

- implantation du logiciel au CNRC à Ottawa et essais d'acceptation;

- démonstration des fonctionnalités du logiciel, utilisant des cas d'espèce;

- rédaction d'un rapport explicitant les procédures utilisées et donnant les principaux résultats obtenus;

- remise au CNRC et au CDT de l'ensemble des logiciels et des documents connexes, c'est-à-dire les manuels d'utilisation, les descriptifs des modèles et une synthèse des fonctionnalités du logiciel, des applications possibles et des données minimales à fournir.

Le comité d'orientation, composé de représentants du CNRC, du CDT et des sociétés ferroviaires, a fait oeuvre utile en déterminant les fonctionnalités voulues du logiciel et, au moment de la vérification, en faisant des commentaires utiles tant sur la démonstration que sur les documents d'accompagnement.

Le produit final a plus que satisfait aux exigences originales, la raison étant en grande partie imputable à l'interruption momentanée de la recherche, qui a permis à DSL d'améliorer le logiciel en le faisant bénéficier des retombées d'un programme de formation pour entreprises commerciales, notamment par le transfert de certains éléments le constituant.

Le CNRC a apporté son concours à cette recherche lors de la définition, de l'exécution et de la formalisation des études de cas d'espèce. Le résultat de cette collaboration est donné en annexe B.

Tous les objectifs fixés à cette recherche ont été soit atteints, soit dépassés.

Un logiciel complet de simulation existe maintenant au CNRC, prêt à être utilisé, ainsi qu'une documentation exhaustive et détaillée complète. Le présent rapport final rend compte de cette recherche et explicite les caractéristiques du logiciel y sont expliqués avec assez de détails pour permettre aux intéressés de se rendre compte si ce logiciel est bien celui qu'il leur faut.

Malgré l'absence de données réelles, récentes et fiables auxquelles les résultats fournis par ce logiciel auraient pu être confrontés et qui auraient permis de le valider, ce dernier est fin prêt à toute recherche sur le comportement dynamique des trains.

Sa convivialité est telle qu'il a déjà attiré un premier utilisateur: la société ferroviaire Quebec North Shore and Labrador.

Si, pour une application particulière, des modifications ou des améliorations étaient nécessaires, le CNRC possède, en plus de son expérience, la documentation qu'il faut pour les réaliser. En effet, cette éventualité avait été, dans la mesure du possible, prévue dès le début et le logiciel élaboré de manière à en faciliter la prise en compte.

Quoi qu'il en soit, DSL sera toujours prête à répondre à tout appel du CNRC dans ce sens.

Il serait néanmoins très utile de pouvoir confronter les résultats théoriques du logiciel à des données réelles et récentes qui les valideraient. Une telle validation ne ferait qu'accroître la crédibilité du logiciel de simulation, dans le contexte, par exemple, d'un litige à caractère juridique ou apparenté, où les données fournies par ce logiciel constitueraient une preuve formelle. L'idéal serait, bien sûr, que les données de validation proviennent d'essais faits sur des matériels ferroviaires modernes et des longs convois.

L'adjonction d'un pupitre de command serait fort utile, surtout aux yeux d'un service d'exploitation désireux de procéder à des simulations de la conduite de trains.

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Appendix A Contents of Manuals

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1. INTRODUCTION

1.1 Project Objectives

The objectives of the project were as follows:

- to develop a real-time simulation program for longitudinal train dynamics and control which provides the ability for the operator to determine dynamic longitudinal forces at couplers and the longitudinal accelerations of cars within the train.

- to set up the model on facilities at the National Research Council of Canada (NRC) so that special research studies may be conducted.

These objectives have been met.

1.2 Overall Objectives

The broader objective of the project was to provide railways and other organizations with a real-time research and simulation capability for longitudinal train action and control.

1.3 Underlying Motivation

Modern North American railroads are responding to a continued pressure to keep their operating costs under control, while facing high costs both for fuel and for the financing of new capital equipment. Changes in equipment design and operational practices characterize their response.

On the equipment design side, major design efforts are being directed to reduce tare weight of vehicles and to reduce aerodynamic drag and rolling resistance. Articulated car designs of many different types are undergoing field tests. Train sets of special equipment including semi-permanently coupled rail cars are in revenue service. Changes such as these can eliminate conventional couplers mechanisms and draft gear. While virtual elimination of conventional mechanisms will only be realized in unit trains, it still remains that articulated vehicles, or blocks of permanently coupled cars, may become routinely handled in interchange service.

These changes relate directly to the physical response of individual cars in a train, as they transmit coupling forces from one car to another. As seen with the introduction of end-of-car hydraulic draft gear in the 1960's, a small number of non-conventional couplings in a train can lead to train dynamics problems. It is therefore essential that the railroads fully evaluate the consequences of changing car weights and couplings before significant numbers of the new vehicles are placed in service.

Canadian railroads must be in a position to evaluate these changes in equipment design in relationship to their own specific operating requirements. The Canadian rail industry must also be able to generate sound technical data to support the development of new designs which will be best suited for Canadian operation.

On the operational side, changes to cut fuel costs are being implemented to the extent current knowledge allows. Efforts are made to dispatch trains and control their locations through signalling so that stops are avoided when possible and uniform running speeds are maintained. Emphasis is put on the reduced use of the train air brakes while locomotives are in traction, and also on the increased use of dynamic braking.

Variations in train handling may present new operating conditions which result in generation of high in-train force levels. In other cases, operating crews, uncertain of the effect train handling variations will have on their safety, stay with handling policies which are not economical. A rigorous analytical study of such operation can lead to handling policies which are both economical and safe.

1.4 Organization of This Report

Chapter 2 of this report covers the accomplishments and end-items produced during the project.

Chapter 3 addresses the capabilities and limitations of the various models contained within the simulator.

Chapter 4 discusses user methodology including the preparation of input data.

Chapters 5 and 6 cover conclusions and recommendations respectively.

1.5 Related Reports and Manuals

This final report addresses the objectives and accomplishments of the project and conclusions and recommendations. It also addresses, at a high level, the functional capabilities of the simulation package and user methodology.

A detailed documentation package was prepared by DSL under this project and provided to NRC and to TDC. While some parts of this documentation package are subject to restricted distribution, it is available at NRC. Further, on-line documentation is available within the software package itself.

For reference, the components of this documentation package are listed in Appendix A to this report.

2. ACCOMPLISHMENTS

2.1 Project Overview

Although it was originally intended to execute the project without interruptions, the completion date was set back in order that the final product would benefit from other simulator projects at DSL. Thus, by delaying completion of the software package, it was possible to introduce a variety of improvements as regards modelling and, to a greater extent, as regards enhancements to the user interface and data preparation tools.

The project was divided into several areas of effort. These are addressed in the following subsections.

2.2 Functional Requirements

Definition of functional requirements addressed two areas:

- Model functionality; and
- User methodology.

The former addressed the content of the outputs to be produced, the required input data, and the performance and constraints (e.g., train length, car parameters, etc.) of the models themselves. The results are summarized in Chapter 3.

Functional requirements relating to user methodology addressed the form and type of output reports which the software would produce, the mechanisms and tools for definition of parametric input data (e.g., track data, train data, locomotive and car parameters) and of operational input data (e.g., in-cab control manipulations). The development of these requirements was based on:

- DSL's extensive experience with simulator users, in particular those at CN Rail (CN) and at the Southern Pacific Transportation Company (SPTCo).

- DSL's experience in discussing user methodology with various railroads, in particular Swedish State Railways (SJ), the Metro-North Commuter Railroad Co. (MNCRC) and the Long Island Rail Road (LIRR), amongst others. The differing requirements of these users was instrumental in allowing the definition of a user methodology and interface which is appropriate to the widest possible range of users.

- Discussions between project personnel and the project steering committee, whose members represent a broad range of potential users of the simulation package to be produced. The committee was composed of representatives of the Canadian rail industry as well as government. These discussions provided some new ideas; these were implemented.

The Functional Requirements are documented in Volume 5 (see Appendix A).

2.3. Software Package

The total software package consists of:

- Data Preparation Utilities and Input Data Files.
  These are the programs used to define parametric data for trains, track, etc. The Input Data Files contain predefined track networks, trains, exercise parameters, vehicle characteristics, etc. The Data Preparation Utilities may be used to modify or add to this database.

- Simulation Session Software
  These are the programs which execute the simulation itself. During simulation, the input of control changes (e.g., throttle, brakes, etc.) can be either interactive or file-driven (i.e., either responsive to the simulator or predefined).

- Data Analysis Software
  This software is used to analyze and present results of a simulation subsequent to the simulation itself (i.e., it is off-line). While some software in this category was supplied under the contract, NRC has added to it subsequently.

The software package was developed at DSL, initially on a PDP 11/34, and later on a MicroVAX II. It was then moved to a VAX 11/780 at NRC's facilities in Ottawa, and later to a VAX workstation (also at NRC). Currently, it is available and running on the workstation.

2.4 Acceptance Testing

Full acceptance tests were run at NRC to ensure that the final product meets all the predefined Functional Requirements and is otherwise acceptable.

2.5 Demonstration to Prospective Users

As representatives of prospective users, the members of the Steering Committee attended demonstrations of the simulator, both at DSL and later at NRC.

2.6 Model and Software Documentation Package

A comprehensive package was supplied both to NRC and to TDC. Appendix A to this report identifies its contents.

2.7 Applications to Date

To date, the NRC system has been used by NRC to evaluate model validity and to compare the performance of these models with others. Appendix B to this report is a note on this subject provided by NRC.

3. MODEL CHARACTERISTICS - CAPABILITIES AND LIMITATIONS

3.1 General

This chapter summarizes the functional characteristics of the models which are contained within the simulator. This information will be most useful to a potential user of the simulator as it is sufficient to allow him to determine whether the outputs produced suit his needs (section 3.2), whether the input data provides the level of detail required for his purpose (section 3.3), and whether the models are suitable (section 3.4). Section 3.5 addresses validation of the models, both inside and outside the scope of this particular project.

3.2 Model Outputs

3.2.1 Train Handling Evaluation

The longitudinal train action model may be operated using a variety of "block lengths". That is, the cars and locomotives in the train may be treated as individual masses with elastic and damping characteristics between each ("single-vehicle blocking") or, for faster operation, multiple cars may be lumped together ("multiple-vehicle blocking").

While multiple-vehicle blocking is useful in doing preliminary studies, single-vehicle blocking provides more accurate in-train forces.

When operated with single-vehicle blocking, in-train forces between each pair of cars are available. While the software as delivered only permitted the force histories to be retained for six couplers within the train, NRC has already alleviated this limit and is continuing to alleviate it further.

Longitudinal vehicle acceleration histories are also available should a user be interested (e.g., to evaluate lading damage).

The ability to record these time histories and to preserve them for subsequent off-line analysis provides maximum flexibility for the application of the user's preferred evaluation methodology.

3.3.2 Parametric Data

Details of the contents of the input files are provided in the manuals; the following subsections provide an overview.

3.3.2.1 Track Data

Every network of track over which simulations are to be run is made up of one or more "track segments". Routes without alternate events (i.e., the ability to allow the simulated train's trajectory to be varied on-line) are simplest, and this is the case for the typical user. The layout of track network is defined in a "Route file".

Data pertaining to the distance-base for each track segment (e.g., subdivision name, starting milepost, etc.) is collected in the "Track Segment Library".

Two other files exist for each track segment. One of these, the Track Profile File, defines track geometry. The other, the Track Plan File, allows graphical information (e.g., location of sidings, signals, etc.) to be displayed on the track profile display during simulation. This latter file is retained purely for compatibility with training simulators; for research and analysis, the data in this file is usually trivial.

The Track Profile File is, however, important to simulation. It contains gradient and curve data for the track. Gradient data is intended to be "design" data rather then measured track profile and consists of a series of locations and the nominal track gradient up to each point. Curve data contains a start of curve location, end of curve location, and nominal curvature for each (horizontal) curve. As the curve data is used solely for display and for rolling resistance, inclusion of details of the spirals was deemed inappropriate.

Track profile data needs to be provided for all track over which movement is to be simulated. The approach defined above means that the acquisition of such data is easy; typically, the required information is available from track plans; track measurement is not required.

3.3.2.2 Train and Vehicle Data

The parametric data for trains and for individual vehicle types are kept in library files.

The train make-up information is kept in the "Consist Library". For each defined train, the library entry simply contains a series of pairs of items. The first of these two is the number of vehicles of the same type (one or more), and the second identifies the vehicle type (i.e., the entry in the vehicle library, described next).

The vehicle library defines the parameters for each of the vehicle types. The first item, vehicle type number, is a unique identifier for the vehicle type (i.e., for this particular set of specifications). The following data are specified for each vehicle type defined:

Entry No.	Contents	Units
1	- Vehicle type number	<->
2	- Vehicle description (a line of text)	<->
3	- Coupled vehicle length	<ft>
4	- Vehicle type code (locomotive, loaded car, empty car, caboose)	<->
5	- Actual gross vehicle weight	<lb>
6	- Nominal gross vehicle weight	<lb>
7	- Design braking ratio (i.e., the braking ratio based on the nominal gross vehicle weight at 50 psig cylinder pressure.)	<%>
8	- Rigging efficiency (also at 50 psig)	<%>
9	- Brake shoe type (composition or cast iron)	<->
10	- Control valve type (ABD, or ABDW)	<->
11	- Draft gear type (friction, rubber, or user-defined)	<->

For locomotives, each entry contains additional data including:

12	- Locomotive type	<->
13	- Indicator for DB-equipped locomotives	<->
14	- Extended range DB option	<->
15	- Recovery after DB option	<->
16	- "Flat" option on dynamic brakes	<->
17	- DB loss on power-knock-down option	<->
18	- Overspeed trip speed limit	<mph>
19	- J-valve type (J-1, J-1.6-16, J-16 (with or without inshot feature), or J-48 (also with or without inshot feature)	<->

3.3.3 Modes of Operation

Depending on the application, the simulator may be operated either in Interactive Mode or in Batch Mode. In many cases, it is convenient to use Interactive Mode for early runs and to use Batch Mode for detailed analysis and for sensitivity studies.

3.3.3.1 Interactive Mode

In interactive mode, the user acts as the locomotive engineer. Using the keyboard, the user himself decides when to enter control changes and what they are. This allows the control input levels, sequence, and timing to be appropriate to the response of the simulated train.

3.3.3.2 Batch Mode

By contrast, in batch mode, the locomotive engineer's inputs are predefined in a file. This allows a simulation run to be repeated, often with changes to the scenario, the train characteristics, or the engineer's control inputs. The major benefit of this mode of operation is to facilitate such controlled experiments. This is particularly useful if detailed results are required and if, as a result, the simulation is operating at less then real time.

3.3.4 Train Control Inputs

The available inputs include all those normally used by the locomotive engineer while operating a real train over the road. All the major control stand inputs (e.g., throttle, reverser, etc.) and air brake inputs (automatic and independent) are provided.

3.3.5 Changing the Simulated Environment

The "Mission Library" is used to define the train to be used (it identifies an entry in the Consist Library), the track to be used (Route number), and the operational parameters at the beginning of the run (starting location and velocity, retainer/handbrake settings, etc.).

Also included are other operational parameters such as:

Nominal wheel/rail adhesion;
Brake system standard pressure;
Brake system leakage rate; and
Coupler force levels at which the train will break in two.

At the beginning of a run, the user is asked for a mission number. This provides a set of default parameters for the upcoming run. At this point, he may either proceed with the run as defined or interactively change any of the run parameters before beginning the run.

If a particular set of parameters is to be reused many times, the user may add a new mission to the library if he wishes. For "one-off" runs, it is usually easier to set the run up interactively based on an existing mission.

The mix of "canned" mission parameters and interactive modifications provides maximum flexibility.

3.4 Models

3.4.1 Models Overview

The models provided include:

- Locomotive Systems
- Air Brakes Systems
- Running Resistance/Gradient
- Net External Forces
- Train Motions

Existing models used in the simulation are based on both theoretical and empirical formulations generated from test data curve fitting and have been extensively tested and proven, both in training and in engineering analysis applications.

The basic models are broken into three categories, namely: (see Figure 3.4-1).

- Component external forces
- Net external forces
- Train motions and coupler forces

In this context all forces are longitudinal ones; external forces are defined as those forces acting longitudinally between the train and the external environment. These exclude coupler forces and inertial forces but include those discussed below.

3.4.1.1 Component External Forces

The locomotive systems model produces the tractive (propulsive) or dynamic braking (retarding) force acting on each locomotive given the current status of the train, current control settings, and the motive power characteristics.

The brake systems model produces the gross available retarding forces for each vehicle in the train given the current status of the train, current control settings, and the vehicle characteristics.

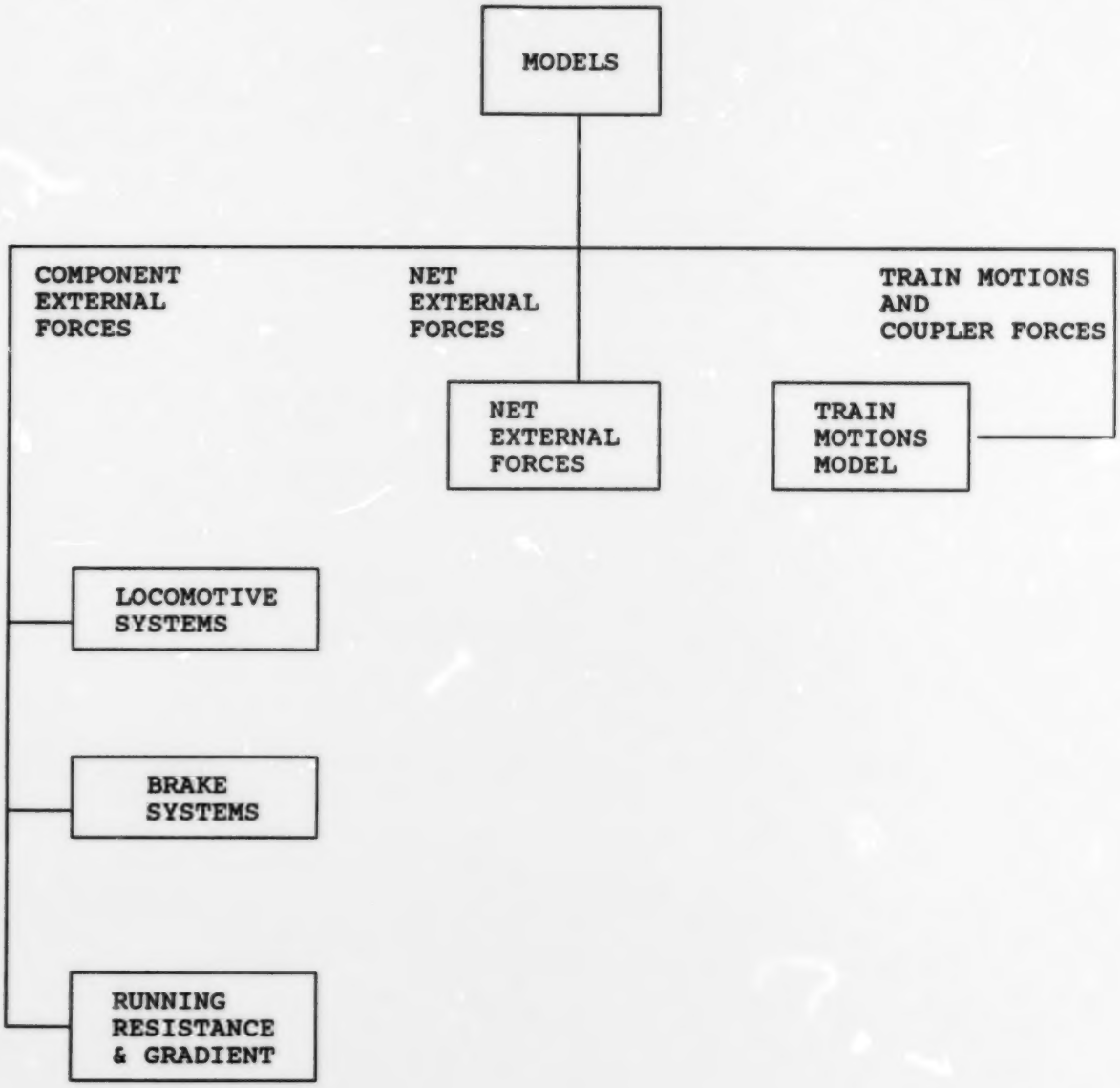

FIGURE 3.4-1

BASIC MODELLING STRUCTURE CHART

The running resistance model produces the gross available retarding forces acting on each vehicle due to windage, straight track rolling resistance, and extra rolling resistance in curves (modified Davis formula).

The gradient model produces the propulsive forces which act on each vehicle in the train due to the inclination (gradient) of the track.

3.4.1.2 Net External Forces

The Net External Forces model produces the net available retarding force and propulsive force on each vehicle given the component forces and information about the motion of the train.

3.4.1.3 Train Motion and Coupler Forces

The Train Motions model produces the location, velocity, and acceleration of the lead locomotive in the train given the net external forces acting on all vehicles in the train. This model also produces the in-train (i.e., coupler) forces and vehicle accelerations.

3.4.2 Locomotives

The locomotive model represents a GM locomotive, the SD40-2 model. There may be up to fifteen of these in any given train and they may be split between a "lead" consist (i.e., one at the head end) and a "remote consist" (i.e., one elsewhere within the train).

In the as-delivered software package, all locomotives respond synchronously. Recent work done for the Quebec North Shore and Labrador Railway (QNS & L) included an upgrade to allow independent motoring of the remote consist; at present, this feature is only available in batch mode.

3.4.3 Air Brakes

The air brakes model handles conventional North American freight brakes (26L system). Both automatic (train) and independent (locomotive) brakes are modelled.

Dynamic brakes are covered by locomotive systems. Control valves on individual vehicles may be specified as either ABD or ABDW and rigging efficiency and braking ratio are specified amongst the vehicle parameters.

On locomotives, options include J-valve type, whether there is independent recovery after DB, and whether there is DB loss on power knock down.

Propagation delays and rise-times are modelled throughout the train. The model treats:

- service applications
- full service
- overreductions
- cycle braking
- emergency
- release and recharge

As a convenience, a facility is available whereby the whole train brake system can be instantaneously released and recharged.

Standard pressure and leakage rate may be specified for any train. Leakage is modelled as being distributed along the train.

3.4.4 Other External Longitudinal Forces

These include forces acting longitudinally on each vehicle due to track gradient and "running resistance".

Track gradient forces are simply the product of gross vehicle weight and track gradient and act on each vehicle in the downhill direction.

Running resistance comprises rolling resistance on tangent track, incremental rolling resistance in curves, and wind resistance. A modified Davis formula is used; different parameters are used for:

- the lead locomotive in the train;
- other locomotives; and
- freight cars.

All forces are calculated for each individual vehicle in the train.

3.4.5 Adhesion

Adhesion refers to wheel/rail adhesion; brake shoe friction is modelled via the vehicle parameters and is not the subject of this section.

In determining the net longitudinal force acting between the wheels and the rail, the tractive forces (for locomotives) and the braking forces (for all vehicles) are considered in combination with the train velocity.

The net wheel/rail force on each vehicle is limited to a proportion of the gross vehicle weight. The proportion is determined by:

- nominal adhesion level (a user-specified parameters);
- train velocity;
- location of the vehicle in the train; and
- sanding on/off.

3.4.6 Longitudinal Train Dynamics

Given the forces discussed above, the role of the longitudinal train action model (LTAM) is to:

- update location and velocity of the train;
- calculate the acceleration of each vehicle (this discussion presumes single-vehicle blocking);
- calculate the longitudinal force in each coupler pair.

Each coupler force is calculated based on:

- the coupler pair characteristics;
- the relative displacement between the two coupled cars (as calculated during the prior iteration); and
- the relative velocity between the two coupled cars (also as calculated during the prior iteration).

These coupler forces, in combination with the component external forces for each vehicle in the train, allow calculation of the net force acting on each vehicle. This force, in combination with the effective vehicle mass, allows the instantaneous absolute acceleration of each vehicle to be calculated and therefore the relative acceleration between each pair of vehicles. This value is then integrated twice to provide relative (i.e., inter-vehicle) velocity and displacement.

The absolute acceleration of the lead locomotive is double integrated to update its absolute velocity and location on track.

Draft gear types currently available include two typical friction types and one rubber type. Slack is adjustable.

3.4.7 Train Motion Modelling Alternatives

The user has the choice of having the train simulated with the train motion model set for longitudinal train action or in the rigid train mode. In the former, all the "blocks" (which may be as small as a single vehicle) are individually modelled and in the latter all the vehicles are grouped together in one rigid mass. The following are notable:

- the rigid train model can be used if in-train forces are not required; this is often useful in early runs.

- when the real time mode of operation has been selected, the longitudinal train action model automatically groups vehicles together into blocks of vehicles and adjust the integration iteration rate so as to be able to operate in real-time, given the limitations of the computer on which the simulation is being performed;

- in order to have individual vehicle modelling, the slower than real-time mode of operation must be selected; and

- data which describes the inter-vehicle actions may be stored for up to six locations in the simulated train.

3.5 Validation of Models

3.5.1 Locomotive Systems Model

The locomotive model is based entirely on formulations and data provided by the locomotive manufacturer. This is a very mature model and has been developed, over many years, for analysis purposes and for use in training simulators, notably those belonging to CN Rail and to SPTCo.

The model includes options which are broadly available (e.g., "flat" and "tapered" dynamic brakes) as well as options specific to CN and to SPTCo. The extended use of this model for training purposes and the fact that it is based on the manufacturers own data ensures that it properly represents the simulated locomotive as regards:

- tractive effort while motoring;
- braking effort during dynamic braking;
- fuel consumption (motoring or dynamic braking); and
- interaction with air brake equipment.

3.5.2 Air Brake Model

DSL's Air Brake Model has a long history, stretching from 1971 to the present. Details of this history are available in "Innovative Applications of Air Brake Simulations", a paper presented to the Air Brake Association in September 1989 by M.H. Kelley, Senior Systems Engineer at DSL.

The model and software have been continuously refined and revalidated through the development of an increasingly powerful model over its history. The original validation was performed against test data obtained from air brake and locomotive manufacturers, and against data obtained on road tests. Enhanced versions have been further validated against air brake rack tests, against other recognized railroad simulation models and against test data from road tests.

Figure 3.5-1 illustrates the design philosophy used to validate and accept models as they develop. The key to DSL's success in validating its models is in the approach of working with the railways at each of the key design stages:

- Data collection;
- Production of Functional Requirements Document;
- Gathering of Acceptance Test Data;
- Production of the Acceptance Test Document, and
- Performance of the Acceptance Tests.

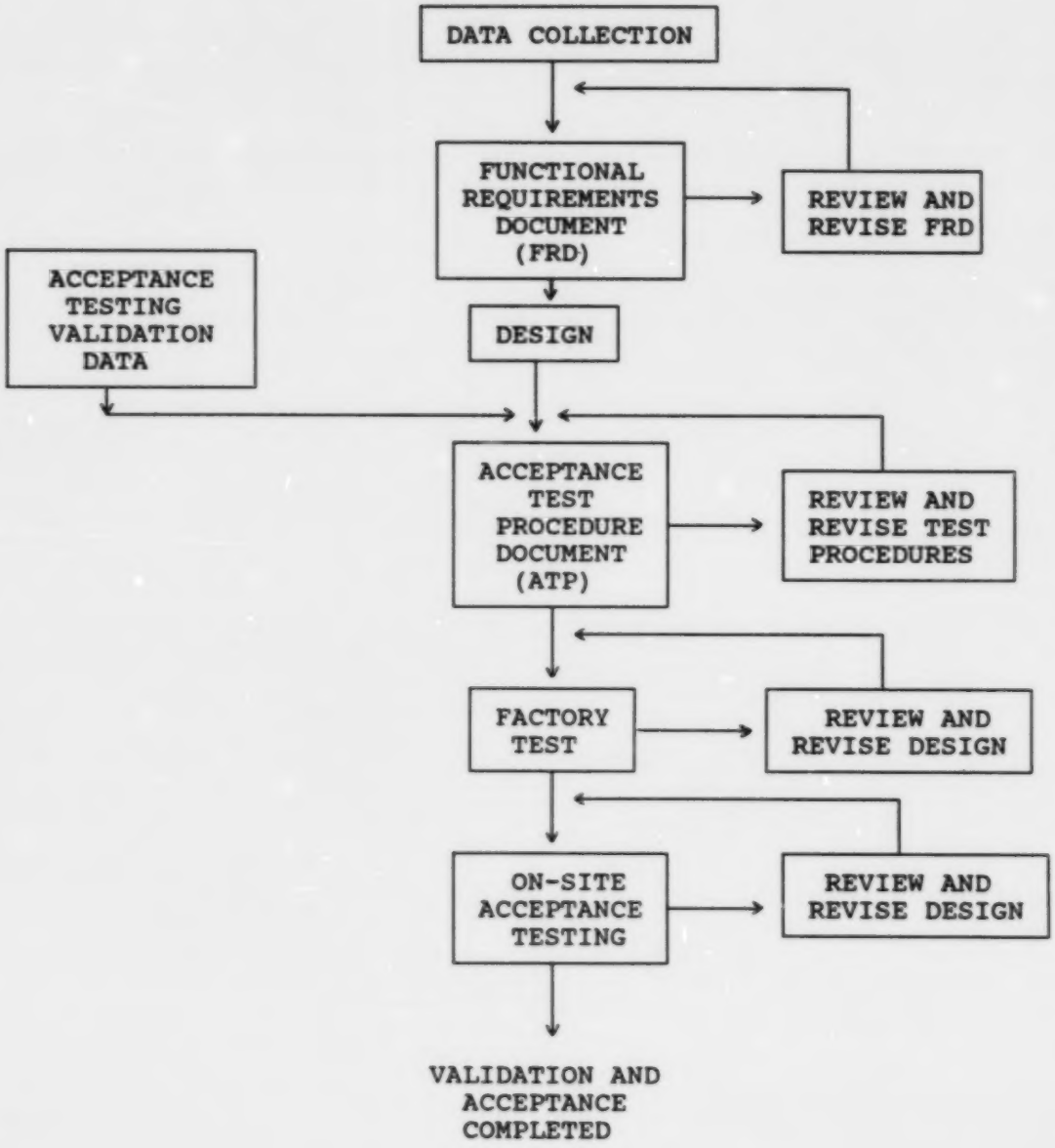

FIGURE 3.5-1

Design Philosophy

Continued testing is performed by each customer to ensure the validity of the simulated train models. In general, each test is intended to be relatively stand-alone so as to facilitate re-runs. This facilitates tests which evaluate the operation of a specific component of the model. Each test is scripted and contains its own set-up procedure. Testing is generally performed for the following areas:

- stopping distance tests involving different brake applications;
- tractive effort tests;
- dynamic brake tests;
- dynamic coupler forces tests; and
- air brake tests.

The following highlights some of the validation and acceptance tests performed on the models during each of the development eras:

- Between 1980 and 1983:
    * WABCO Test Rack Data on different size trains,
    * CN Road Test
    * Stand alone 26-L Brake Equipment
    * Existing previously validated CN models

- Between 1983 and 1986:
    * SP WABCO Test Rack Data
    * SP Road Test
    * SP Standing Air Brake Tests on freight trains after acceptance.
    * Comparison to other software packages.

- Between 1987 and 1989:
    * CN Road Tests
    * CN WABCO Test Rack Data
    * Other CN Software Packages
    * CN's Hybrid Train Dynamics Computer

3.5.3 Longitudinal Train Action Model

A discussion of the validation of this model is included in appendix B to this report.

4. USER METHODOLOGY

4.1 General

Effort was addressed to ensuring that the user interface to the software package would be straightforward and convenient, would provide the desired functionality as delivered, and would allow for ongoing upgrades and enhancements, particularly as regards output of results. This effort was successful.

Often with simulation of the operation of trains over various routes, the collection, organization, and entry of the input data parameters can be onerous. Since the objective was to provide a tool to industry that would actually be used, attention was directed toward making this aspect of the simulator as easy to use as possible.

4.2 Prior to System Design

The project was fortunate to have a steering committee whose members were knowledgeable of, and experienced in, the development and application of simulation packages.

Their input, in conjunction with DSL's extensive experience with a variety of users (including CN, SPTCo, Swedish State Railways, etc.), ensured the development of an excellent set of user interface requirements. The final product conforms to these requirements and combines a broad (and therefore powerful) range of input data with ease of use. Further, all user input data, mechanisms, and conventions are well documented.

4.3 Industry Demonstration and Response

An early demonstration of the simulator (at DSL late in the development stage) was presented to members of the steering committee in their role as representatives of industry. This occurred on August 27, 1986.

Subsequent to this demonstration, comments were received from various of the members.

In general, it was agreed that the package conformed to the predefined Functional Requirements. Most of the comments were related, not to the performance of the simulator itself, but rather to deficiencies in the clarity and completeness of the draft documentation. These deficiencies have since been rectified. Other comments related to validation, addressed in section 3.5 above.

Other comments suggested future upgrades to the model capabilities (e.g., the incorporation of zero-slack inter-car couplings).

The comments were addressed and a subsequent demonstration of the simulation package was performed at the final acceptance tests conducted after installation of the finished software package of NRC. Steering committee members, and others, from both NRC and TDC, were entirely satisfied. On the basis of these tests/demonstrations, the final package was accepted.

4.4 Real-Time Capabilities and Limitations

Based largely on comments from the steering committee members, the capability of the simulator was upgraded so that it could operate either:

- at a rate proportional to real-time, or
- as fast as possible given the available computer resources.

The only limitation at present is that, with the computer which is currently being used, it is not possible to combine real-time operation and single-car blocking. The effects of this limitation are minimal, however, in that preliminary runs may be made, in real time, using larger blocks. This allows the user to define the set and sequence of desired control inputs for the runs. Final analysis runs may then be duplicated in batch mode, at less than real time, if single-car blocking results are desired.

4.5 Preparation of Input Data

4.5.1 General

The simulator requires two types of input data; "parametric" inputs which are specified prior to simulation and are fixed (e.g., track geometry data), and "control" inputs which are normally provided interactively at the time of the simulation by the user (e.g., locomotive control manipulations).

A large amount of parametric input data is required, both to describe the train being simulated (including characteristics of individual locomotives and cars), and to describe the track over which the simulated train is to operate. Often, however, the same parametric data may be useful for many simulation runs. This being the case, parametric inputs are prepared prior to simulation (during the "preparation" phase), and are kept in files.

Optionally, much of the control input data may also be predefined. This is accomplished with the "Batch" files.

4.5.2 Approach

Generally, the user specifies the data in the form of a "source" file, a file which can be listed, edited, and displayed conveniently using any standard editor. This form of file is user-oriented.

However, this form is not convenient for use at run-time since, amongst other reasons, it can only be accessed sequentially. This being the case, source files are converted to "run-time" files using the "utility" programs, and it is these run-time files which are used during the simulation itself. The utility programs provide not only this conversion but also error checking; they may also be used to read the created run-time files and to display their contents, either to a terminal or to hard copy.

In the context of this simulator, the term "library" is often applied to a file which contains a collection of entries (e.g., the Vehicle Library).

4.5.3 Types of Input Files

Figure 4.5-1 shows the hierarchical relationship between the various types of input files. The nature of the relationship between file types is explained next.

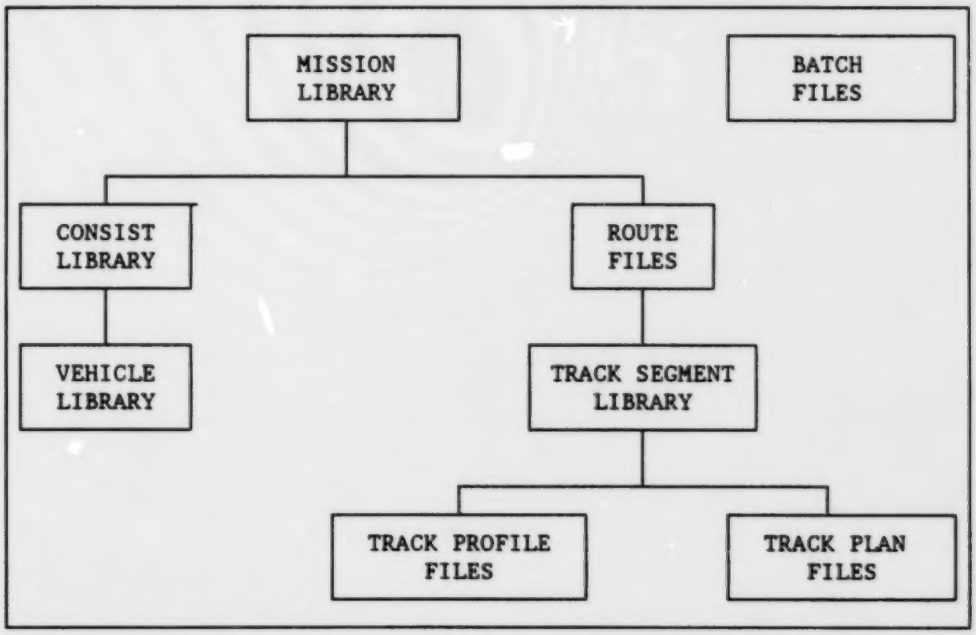

Figure 4.5-1 Input File Hierarchy

The information in a mission library entry specifies, amongst other things, a consist number and a route number which identify entries in the consist file and a particular route file respectively. Similarly, the information in a consist library entry specifies a series of vehicle numbers which identify entries in the vehicle library, and the information in the route file specifies a series of track segments which make up the route. The information in a track segment library entry identifies, in turn, the track profile file and track plan file appropriate to that track segment.

4.5.4 Description of Input Data File Types

4.5.4.1 Mission Library

Each entry in the mission file provides a top level run specification including information such as consist number, route number, nominal track adhesion, brake system leakage rate, starting location on track, etc. Whenever a new mission is started, the user is first prompted to provide a mission number. The session software then goes into the mission library and extracts the set of parameters for the specified mission. These values are used to fill in default values in the run specification form. This form is then presented to the user to allow him to modify any parameters that he wishes (e.g., a different starting location, alternate consist, etc.). The mission library is the only file which contains such top-level specifications.

All default mission specifications are contained in the "Mission Library", with each such specification uniquely identified by a Mission number.

4.5.4.2 Consist Library

Each entry in this file is identified by a unique consist number and indicates the makeup of a complete train, from front to rear, by specifying, for each string of one or more identical adjacent vehicles, the number of identical vehicles and the "vehicle number", the latter being a reference into the vehicle library.

4.5.4.3 Vehicle Library

Each entry in the vehicle library is identified by a unique "vehicle number" and contains, for that vehicle type, the relevant parameters describing the particular characteristics of that vehicle type (e.g., length, weight, braking ratio, etc.).

4.5.4.4 Route Files

The purpose of a route file is to define, at the highest level, a network of track over which an exercise may be run. There is a unique route file for each defined network.

Each route file defines the makeup of a network of track by defining how various "track segments" may be strung together. At its simplest, a route may contain only a single track segment. However, complicated routes may be constructed which include multiple nested alternate paths ("alternate events").

4.5.4.5 Track Segment Library

This file contains a block of information for each track segment in all defined routes (each track segment is identified by a unique number).

This information relates to the distance base for the track segment and allows conversion between "distance into the segment" (known as track segment chainage) and the user-oriented location base (i.e., subdivision name and milepost).

4.5.4.6 Track Profile Files

Each track profile file defines the gradient and the horizontal curvature along a complete track segment.

4.5.4.7 Track Plan Files

During the simulation, a graphic display of the track is presented on the "track display". This display shows mileboards, track profile, train length and location, and track plan (sidings, diamonds, switches, stations, etc.).

Each track plan file contains all the data required to draw the track plan portion of the track display for a complete track segment.

4.5.4.8 Batch Files

The use of batch files is optional. If the simulator is run interactively, they are not used.

A batch file is a collection of locomotive controls and special events which runs the simulator on its own without the need of a user for input. This allows the user to specify a certain sequence of events in a file and use the file many times over for repeatability. Alternatively, they can be used to do sensitivity analyses. By changing only one or two control inputs (as to magnitude or time/location of initiation), controlled experiments may be run.

All of the locomotive controls and special events available during a run can be put into a batch file. Each locomotive control or special event is specified as to a time or location at which it is to be applied.

Any number of batch files may be defined.

4.6 Access to the Model

Anyone interested in using the simulator or in further information may contact:

Dr. Vincent Thomson
Head of Systems Laboratory
National Research Council of Canada
Montreal Road
Ottawa, Ontario
K1A 0R6

(613) 993-9461

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5. CONCLUSIONS

The project was successful in meeting its objectives. Although thorough validation is frustrated by a lack of recent credible data against which to compare the results of simulation, the simulator may be used profitably for investigations into the dynamic longitudinal behavior of trains.

The ease of use of the simulator will attract users; as evidence, it has already been used by the Quebec North Shore and Labrador Railway.

If, for some special application, modifications or enhancements are required, those at NRC have sufficient documentation and experience to implement the changes. Wherever they were foreseeable, the software has been designed to permit such additions to be implemented easily.

In the event that NRC is unable to effect a particular modification, DSL is available to support them as required.

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6. RECOMMENDATIONS

The acquisition of current valid test data against which the models can be better validated would be welcome. This would enhance the credibility of simulation results, an important aspect if, for example, such results are to be used as formal evidence in a legal or paralegal context. Such test data should, ideally, cover modern equipment and long trains.

The additions of a control stand would render the simulator more realistic. If railway operating personnel are to control the simulated trains, this would be a definite asset.

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APPENDIX A

CONTENTS OF MANUALS

This appendix lists and identifies the detailed documentation for the simulator. These manuals are available at NRC.

TRAIN DYNAMICS SIMULATION MANUALS

Volume 1: (Final Report)
Comments: This document
Distribution: General

Volume 2: Simulator Operator's Manual
Comments: draft dated August 25, 1987
Distribution: Restricted

Volume 3: Input Data Files and Utilities - Operator's Manual
Comments: draft dated August 31, 1987
Distribution: Restricted

Volume 4: Acceptance Test Procedures Part 1 of 3
Comments: draft dated September 1, 1987
Distribution: Restricted

Volume 4: Acceptance Test Procedures Part 2 of 3
Appendices A through G

Volume 4: Acceptance Test Procedures Part 3 of 3
Appendices H and I

Volume 5: Functional Requirements
Distribution: Restricted

Volume 6: Installation Manual
Distribution: Restricted

Volume 7: Development Manual
Comments: draft dated September 21, 1987
Distribution: Restricted

Volume 8: Capability and Applications Document
distribution: General

Volume 9: Technical Reference Manual
Book 1: Parts 1 to 2.2
Book 2: Part 2.3
Book 3: Parts 2.4 to 3, plus Appendices A to E
Distribution: Restricted

APPENDIX B

NRC NOTE ON VALIDATION

This appendix contains a note, prepared by NRC, on validation of the Train Action Model.

The "note" consists of:

- 4 pages of text;
- Figures 1 through 14 (14 pages); and
- an Appendix to the note, consisting of:

  . a cover page;
  . 2 pages of text;
  . track profile (1 page); and
  . 7 figures (7 pages).

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22 September 1989

A NOTE ON VALIDATION OF THE DSL LONGITUDINAL TRAIN ACTION MODEL

P.A. Hamill and R.V. Dukkipati
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National Research Council of Canada

BACKGROUND

The DSL Train Action Model was developed to be the driving software for real time Training Simulators. DSL have built and sold a number of these to client railways in the US, Sweden and Canada and have continued to develop the software to meet the needs of new clients in their international market.

The DSL software has been tailored and tuned to the satisfaction of various railways around the world who have paid considerable money to get a physical representation of their equipment which is acceptable to their own operators for training purposes. This is an extremely demanding audience and DSL's success is a measure of the validity of the train dynamics model as a replication of the equipment,components and operating practice on a number of different railways.

NRC Systems Laboratory acquired the DSL software in December 1987 and have been its custodian since that time. The idea was to evaluate its potential use and make it available as needed for NRC R&D on train dynamics and in response to requests and needs of the Canadian Railway industry and Transport Canada.

NRC have used the model for some (4) useful studies for the industry and government agencies and there is a continuing interest from NTA in the use of simulation as an aid to incident investigation. However there has not been much demand for NRC to use the DSL model for Canadian Railway industry projects. Many Canadian railways have their own capability in this area. CN, for example, use a tailored version of the DSL software for their investigations and have purchased the DSL Simulator for their operator training. Others have had access to and have used the AAR TOS model or the FREIGHTMASTER simulator.

In the meantime AAR have continued with development of the TOES simulation which is now available at very modest cost to members in various PC versions. Some limited but credible validation has been done of the Air Brake Model and Conventional Draft Gear Coupling model and a reasonable level of confidence in the predictive accuracy of TOES has been established. Controlled test series are in progress in 1989 and revenue-service tests are to be done in 1990. It appears that TOES is destined to become the industry standard for modelling of longitudinal train dynamics in North America within the next year or so.

In the absence of experimental data, for example on coupler force measurements, to use for validation, NRC has had to use whatever data was available. This and the evolution of the AAR models noted above suggested that comparisons between the DSL model and documented work on the AAR TOS model would be useful.

This note presents the results obtained from the DSL TAM and the AAR TOS models for Events 6 and 12 of the SP Steel Coil Train Tests which were reported by Martin and Tideman (1977) and by Low and Garg (1978).

These tests were done in 1973 and are fully reported in the above References. Only a brief description will be given here.

The Consist of the SP Steel Coil Train is listed in the Appendix. (pages 3 and 4 from the 1978 Reference)

SIMULATION OF SP STEEL COIL TRAIN EVENT 6

Event 6 was an Emergency Brake Application at a specific mile post while the train was maintaining a steady speed of 40 mph. The track was straight and level. To quote from the 1977 reference; "The locomotives were bailed off almost immediately to avoid a severe run-in from the rear. Then, in addition to the automatic (train) brakes, the independent brake was operated until the whole train came to a stop." (1977)

The SP Steel Coil Train experimental results for Event 6 are no longer considered by AAR to be reliable for validation purposes. The objective here is to compare two simulations of the event.

This event was simulated using DSL TAM and the AAR TOS models and the results are graphically presented in Figures 1 to 7.

Emergency Brake application is at time 0 seconds.

Figure 1 shows train speed in mph vs time in seconds.

Figure 2 shows distance travelled in miles vs time in seconds.

Figures 3 to 7 show coupler force in kips vs time in seconds for Cars Number # 1, 11, 21, 31, 41, and 51.

The following comments are relevant:

The DSL TAM and the AAR TOS models give essentially the same results (Figures 1 and 2) for stopping time and distance and for speed and distance as a function of time.

Agreement between DSL TAM and AAR TOS coupler forces (Figures 3 to 7) is, qualitatively, excellent. Run-in spikes occur at the same time with both models. Buff forces are higher with the AAR TOS model and, in general, the TOS dynamics appear more "lively" than the DSL TAM. It should be noted here that there would be no difficulty in "tuning" the DSL model to get far better quantitative agreement with the TOS results. One of the criticisms of simulation is that it is possible to get almost any required result. The DSL model, as delivered, had been "tuned" to replicate specific known train dynamic characteristics and, until better experimental data is available, this model will be regarded as the DSL standard model.

SIMULATION OF SP STEEL COIL TRAIN EVENT 12

The following is transcribed from the 1978 Reference:

Event 12 involves normal train handling without the use of air brakes. The train proceeded downhill in dynamic braking, through a level section in idle and up a grade with gradually increasing throttle.

The throttle manipulation sequence which was input is:

Start @ MP 1033.11 in Dynamic 7 @ 44mph and continue fo 32 sec.
Dynamic 5 for 1 sec
Dynamic 4 for 1 sec
Dynamic 3 for 1 sec
Dynamic 2 for 1 sec
Dynamic 1 for 13 sec
(Dynamic brake settings obtained from amperage data)
Idle for 15 sec
Run 1 for 11 sec
Run 2 for 7 sec
Run 3 for 6 sec
Run 4 for 10 sec
Run 5 for 9 sec
Run 6 for 11 sec

The track profile involved in this event is shown in the Appendix. (Figure 1 from page 12 of the 1978 Reference)

Figures 9 to 14 show coupler force in kips as a function of time in seconds for Cars # 1, 11, 21, 31, 41, and 51.

The agreement between the DSL TAM and the AAR TOS models is very good. Again the TOS simulation gives more lively dynamics with higher coupler forces but the essential character and the timing of the dynamics of Event 12 is the same on both models. Also there would be no difficulty in "tuning" the DSL TAM simulation to get better agreement.

In the case of Event 12 the experimental results are regarded as credible for validation purposes and the comparison between TOS and the TEST results are reproduced from the 1978 Report in the Appendix.(Figures 3 to 8 from pages 14 to 19 of the 1978 Reference)

As noted in the 1978 reference: " Agreement is generally good with the exception of a run-in spike shown by the TOS commencing at 73 seconds on car 1 and continuing through the consist for 15 seconds." This is most pronounced for Car # 51 (Figure 8 of the Reference) and, as an illustration of the efficacy of "tuning", a plausible variation in the resistance formula was introduced which produced Figure 15 of the Reference giving much better agreement between TOS and TEST for Car 51.

CONCLUSION

A word of caution may be in order at this juncture. It is of vital importance that the limitations of computer modelling and simulation be fully appreciated. The mathematical representation of a complex engineering system is, at best, only an approximation of the real physical system. There are practical limitations to the amount of detail which can be included in a model and in the representation of all the physical phenomena which may effect the system behaviour. The accuracy of dynamic models of vehicles and trains is totally dependent on the data available to represent numerically the behaviour of its components. In the case of the longitudinal dynamics of a train there is a requirement to supply numbers for locomotive propulsion, braking, resistance and coupling characteristics; to braking, resistance and coupling for all vehicles; to track gradient and curvature and to event recorder data available for the specific study being done. Assuming that all the nominal,(as-new or as-designed), values are available,the actual train consist under investigation may not and probably will not be properly modelled because the real components have values different from the nominal values due to age, wear or damage. In a specific case it may be possible to "tune" the model to replicate propulsion, braking and handling of a train if there is good running data for the specific case or for a similar consist with similar components. But prediction of absolute values of, for example, coupler forces must be treated with considerable caution unless reliable experimental data supports the predictions of the simulation. This is rarely the case.

The results of the present study show that the DSL TAM and the AAR TOS models are in very good agreement for two Events that included train operations which are representative and which exercised the models in a demanding manner.

Better quantitative agreement between the two models could be achieved by introducing plausible variations in resistance formulae, damping factors and other "fuzzy" variables but this should await availability of better experimental data.

In the meantime the DSL TAM may be used with confidence for the study of relative effects in longitudinal train dynamics. This is the proper role of simulation.

In cases where good field data allows specific event tuning it should be possible to make credible predictions of train behaviour.

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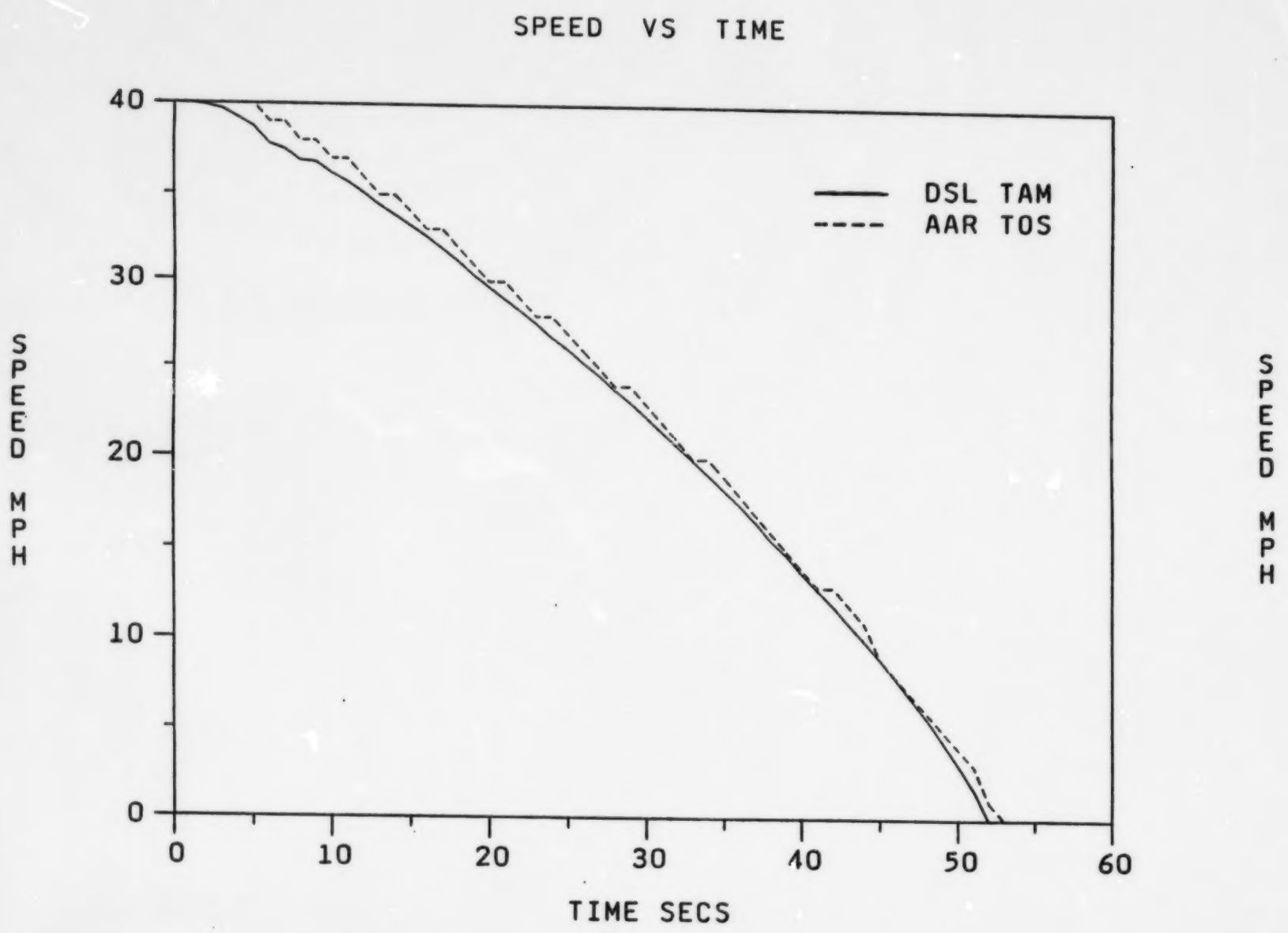
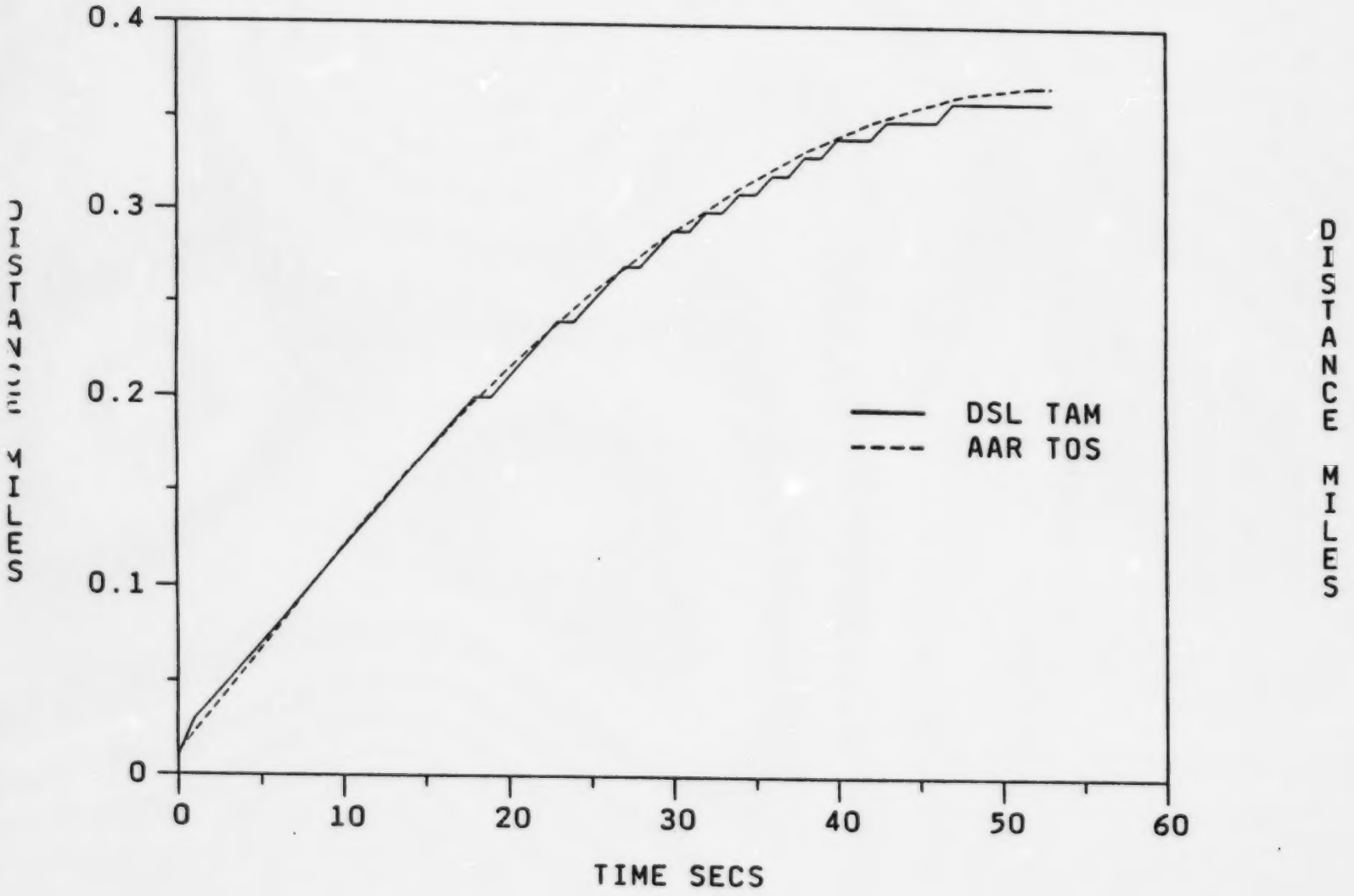
LOW,E.M., and GARG,V.K.
1978. Validation of the Train Operations Simulator Computer Program. Association of American Railroads Report No. R-335.

Martin,G.C. and Tideman,H.
1977. Detailed Longitudinal Train Action Model.
Association of American Railroads Report No. R-221.



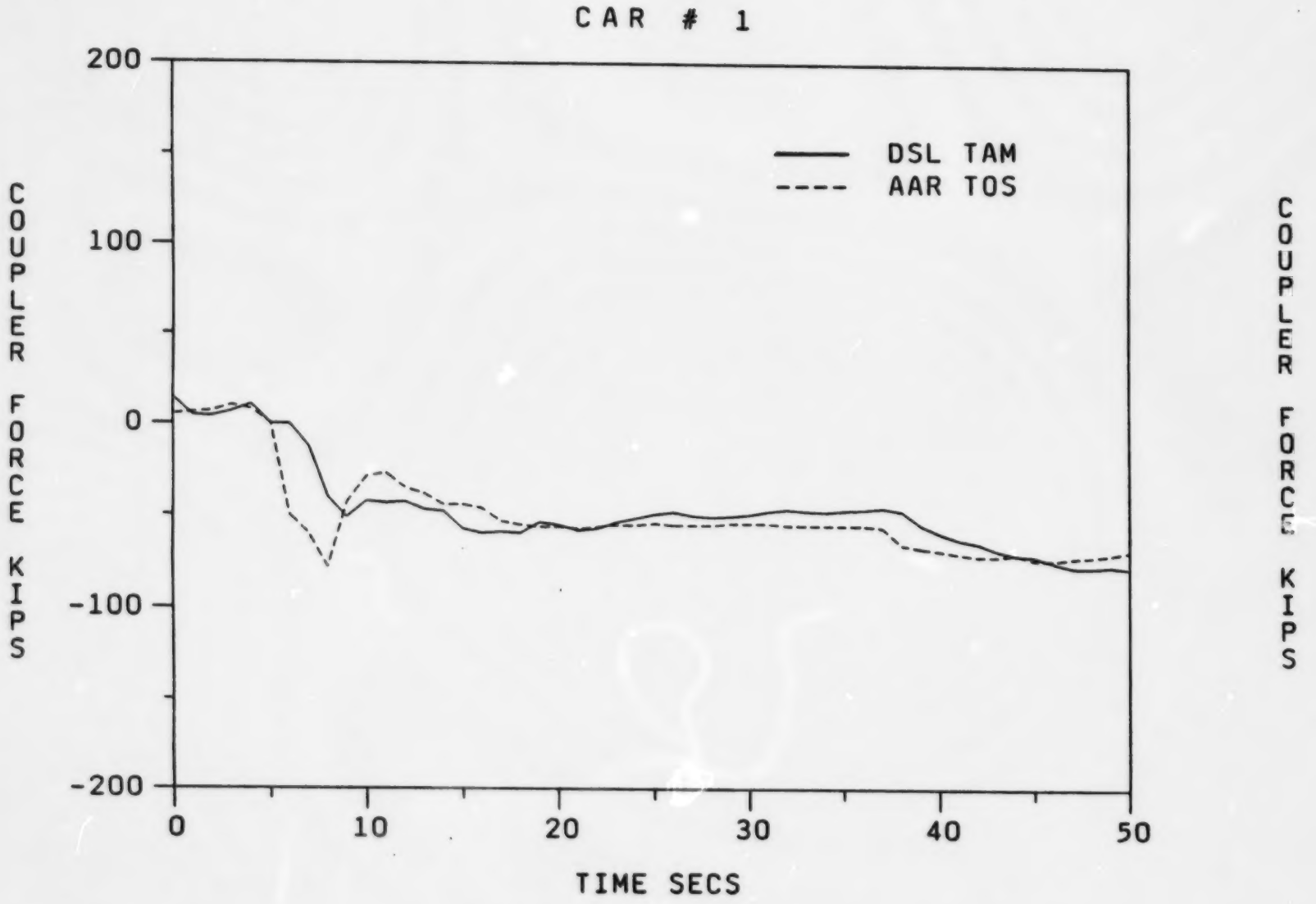
DSL TAM AND AAR TOS SIMULATION OF SP SPRING COIL TRAIN EVENT 6
EMERGENCY STOP FROM 40 MPH ON STRAIGHT LEVEL TRACK

FIGURE 1



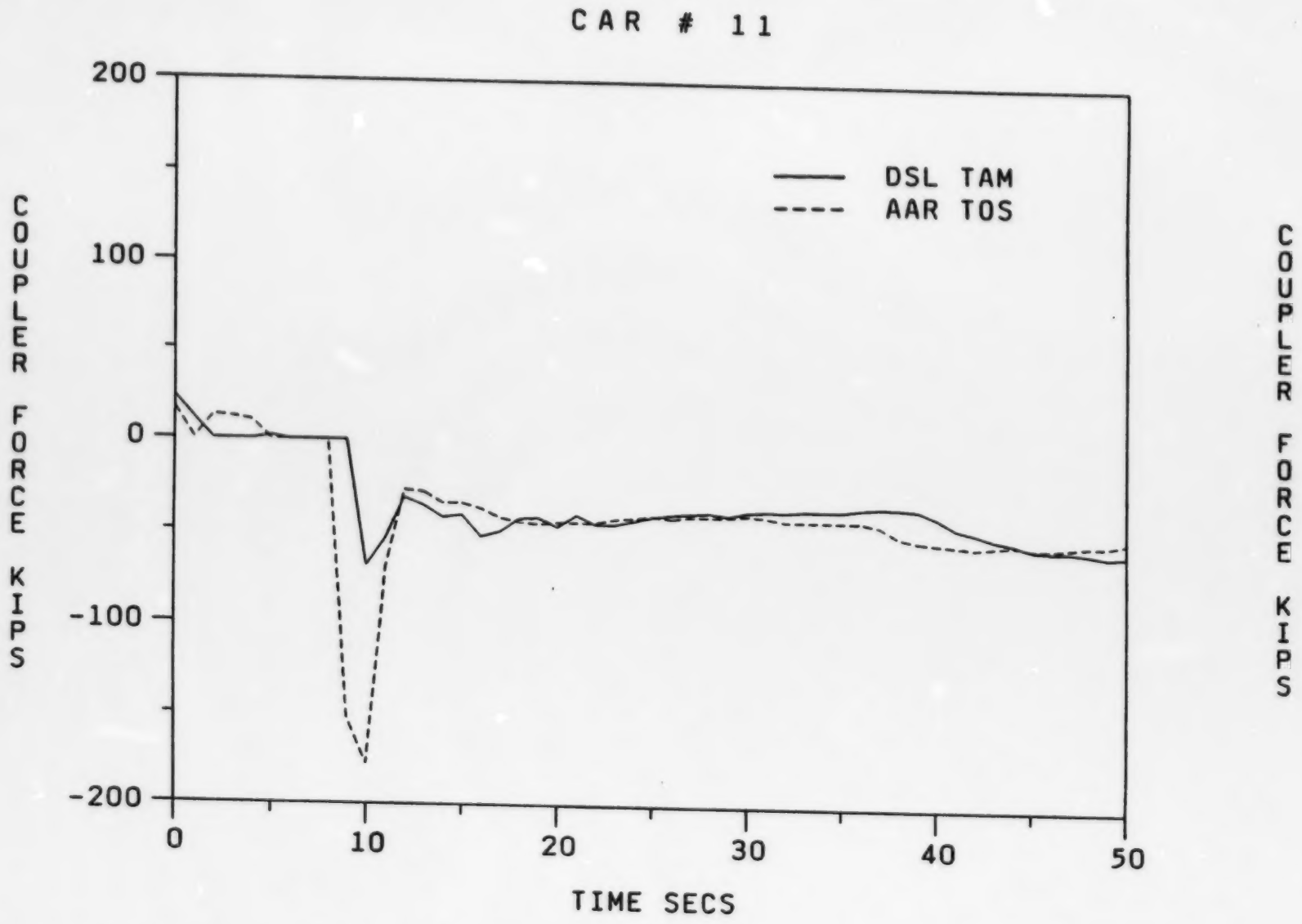
DSL TAM AND AAR TOS SIMULATION OF SP SPRING COIL TRAIN EVENT 6
EMERGENCY STOP FROM 40 MPH ON STRAIGHT LEVEL TRACK

FIGURE 2



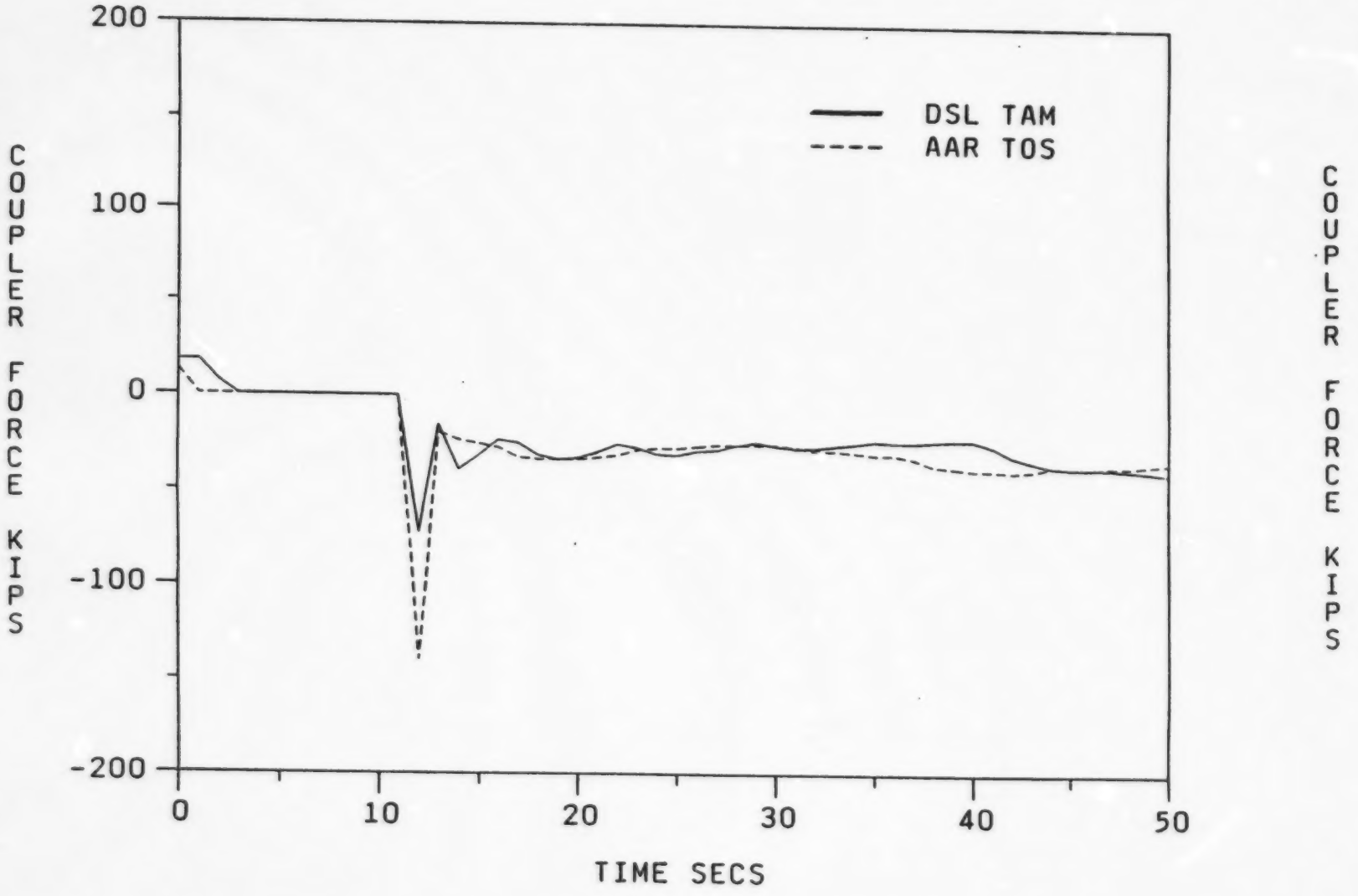
DSL TAM AND AAR TOS SIMULATION OF SP SPRING COIL TRAIN EVENT 6

FIGURE 3



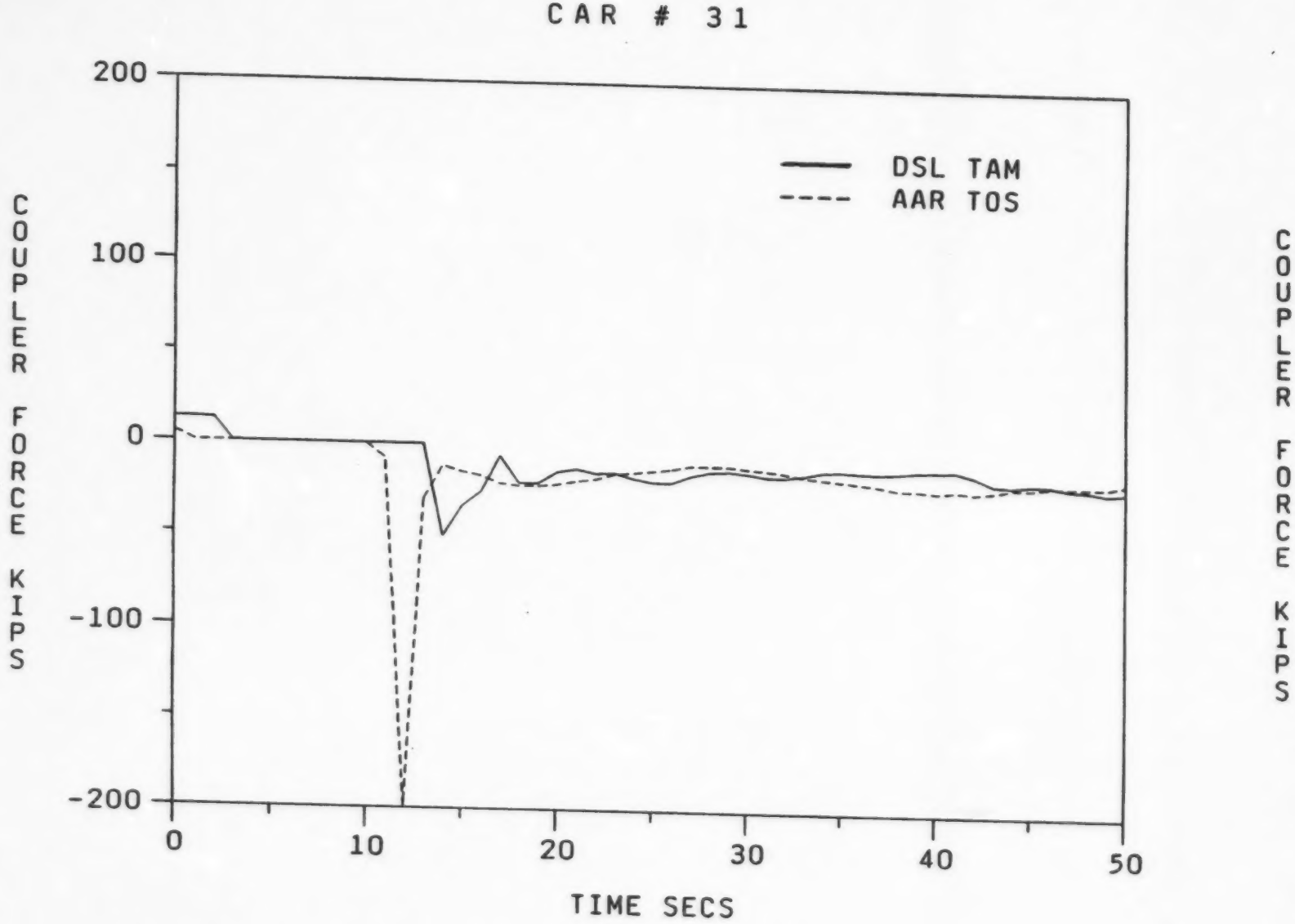
DSL TAM AND AAR TOS SIMULATION OF SP SPRING COIL TRAIN EVENT 6

FIGURE 4



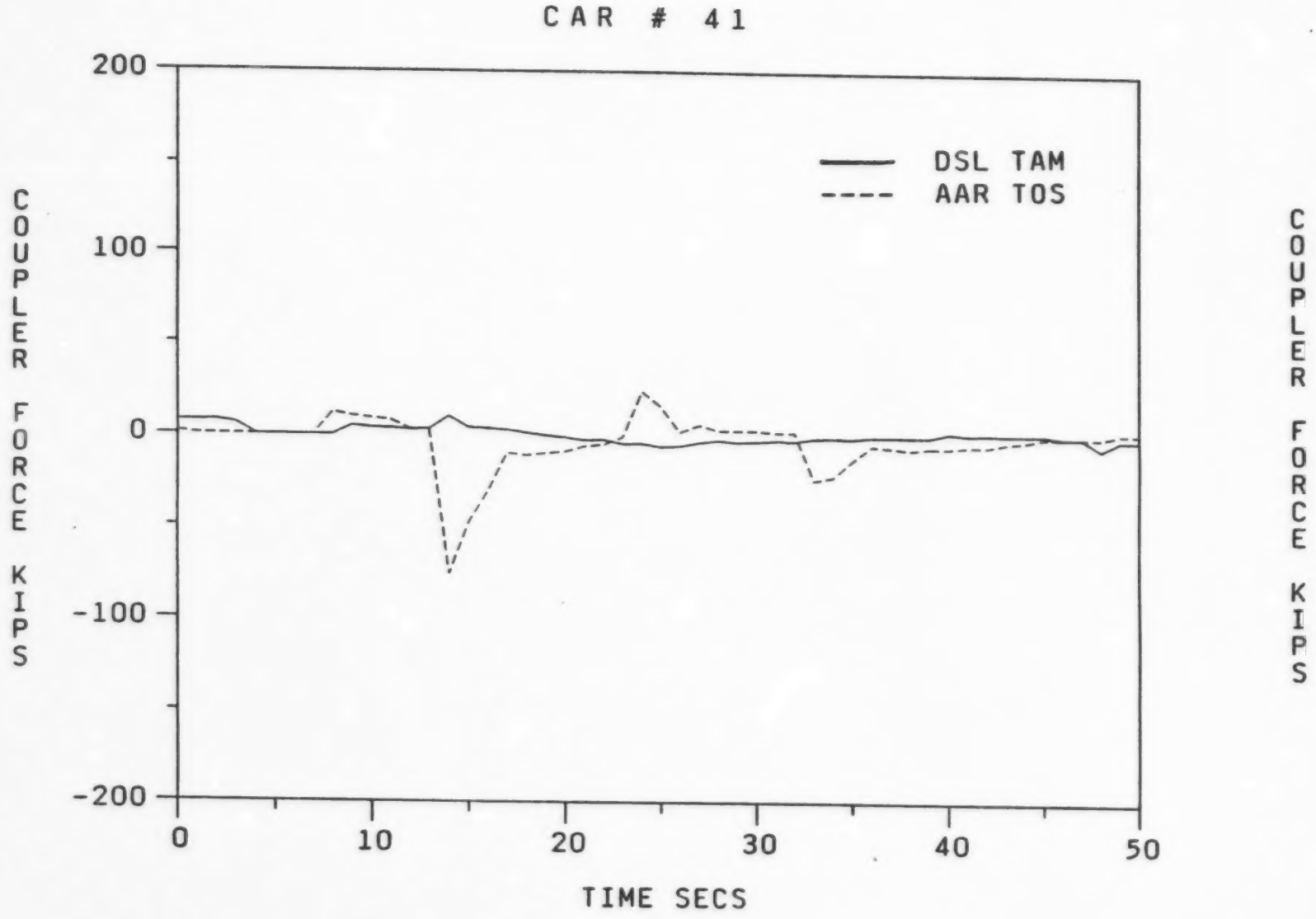
DSL TAM AND AAR TOS SIMULATION OF SP SPRING COIL TRAIN EVENT 6

FIGURE 5



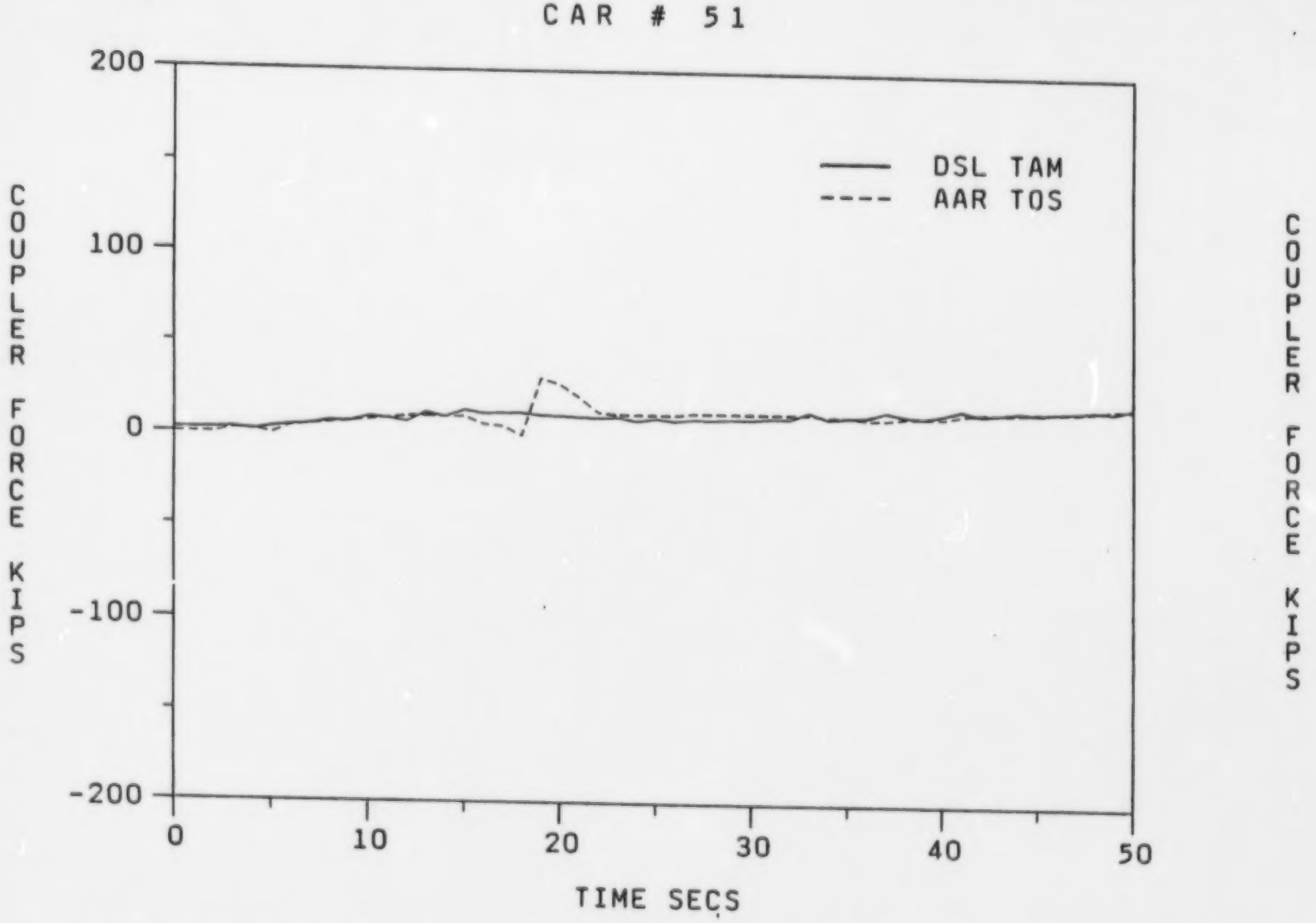
DSL TAM AND AAR TOS SIMULATION OF SP SPRING COIL TRAIN EVENT 6

FIGURE 6



DSL TAM AND AAR TOS SIMULATION OF SP SPRING COIL TRAIN EVENT 6

FIGURE 7



DSL TAM AND AAR TOS SIMULATION OF SP SPRING COIL TRAIN EVENT 6

FIGURE 8

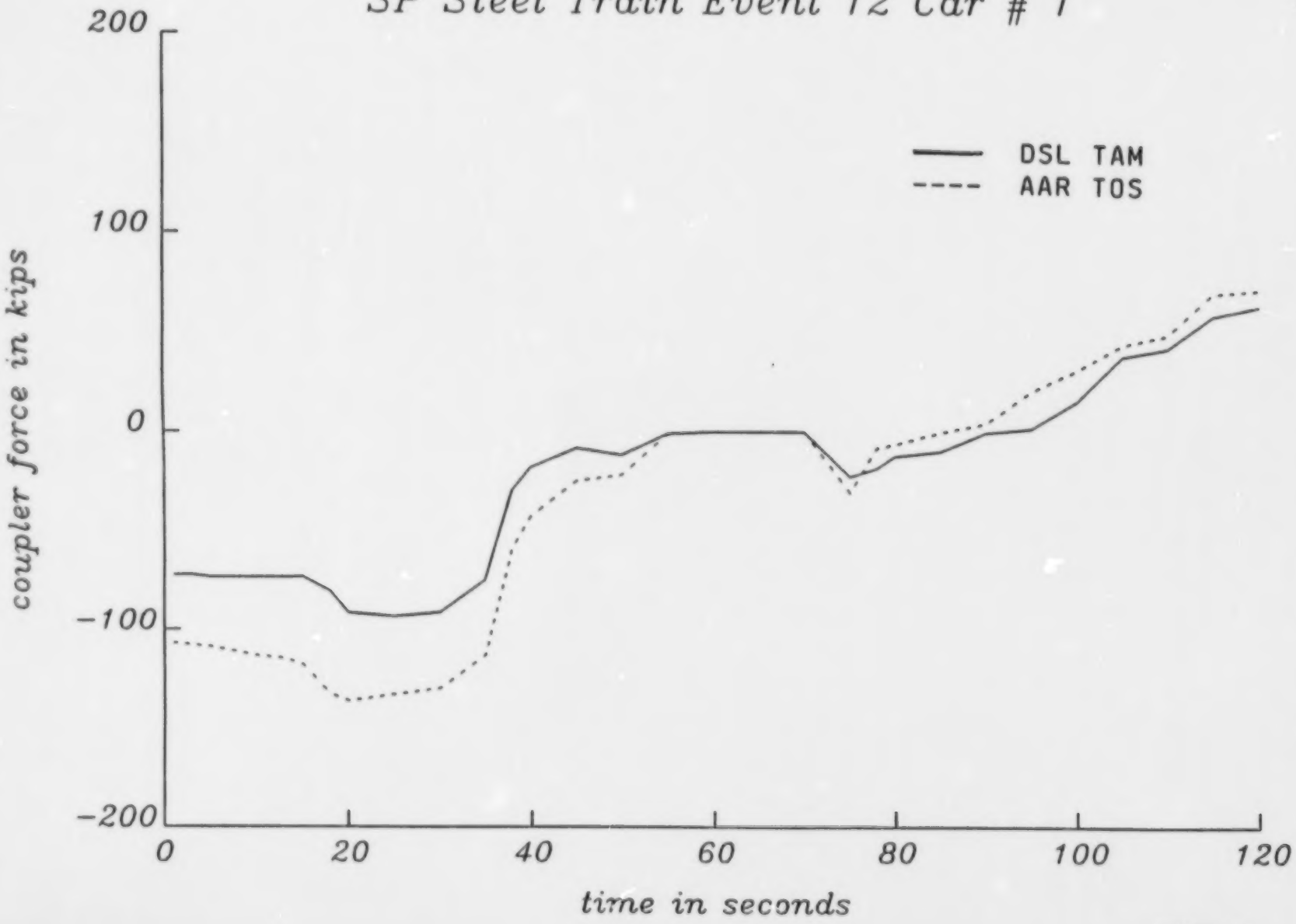

SP Steel Train Event 12 Car # 1
DSL TAM
AAR TOS
coupler force in kips
200
100
0
-100
-200
0
20
40
60
80
100
120
time in seconds

FIGURE 9

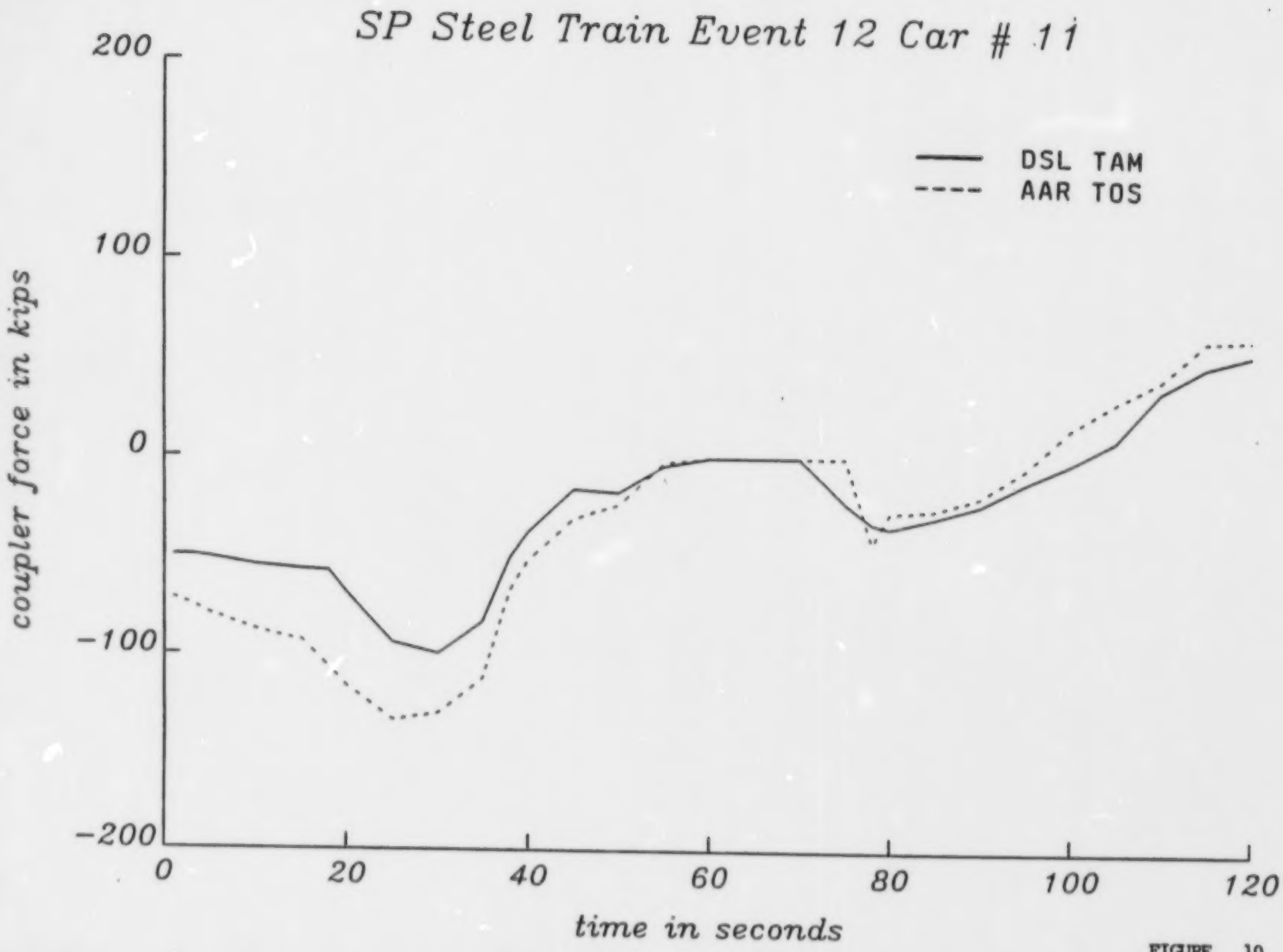

SP Steel Train Event 12 Car # 11
DSL TAM
AAR TOS
coupler force in kips
200
100
0
-100
-200
0
20
40
60
80
100
120
time in seconds

FIGURE 10

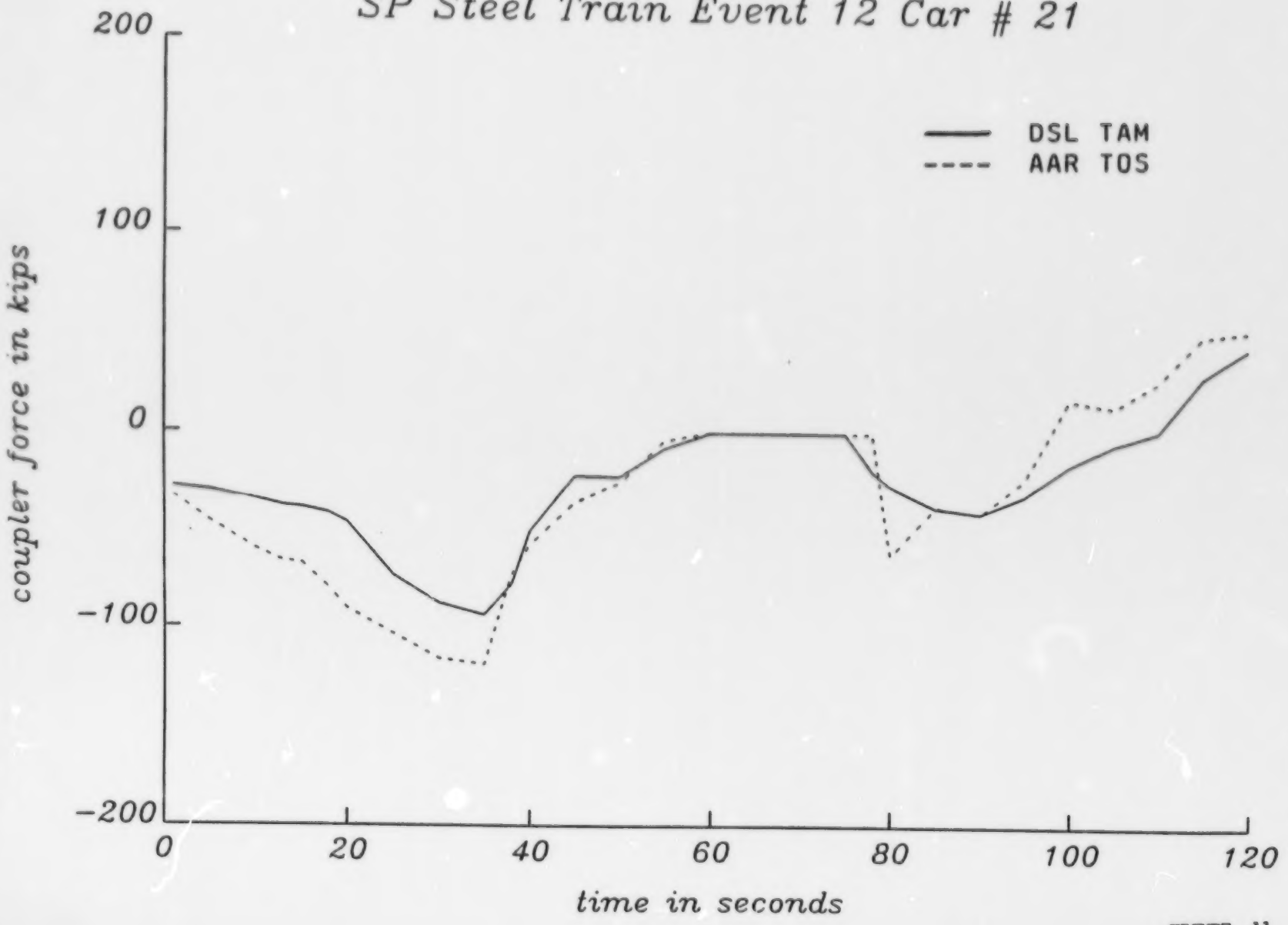

SP Steel Train Event 12 Car # 21
DSL TAM
AAR TOS
coupler force in kips
200
100
0
-100
-200
0
20
40
60
80
100
120
time in seconds

FIGURE 11

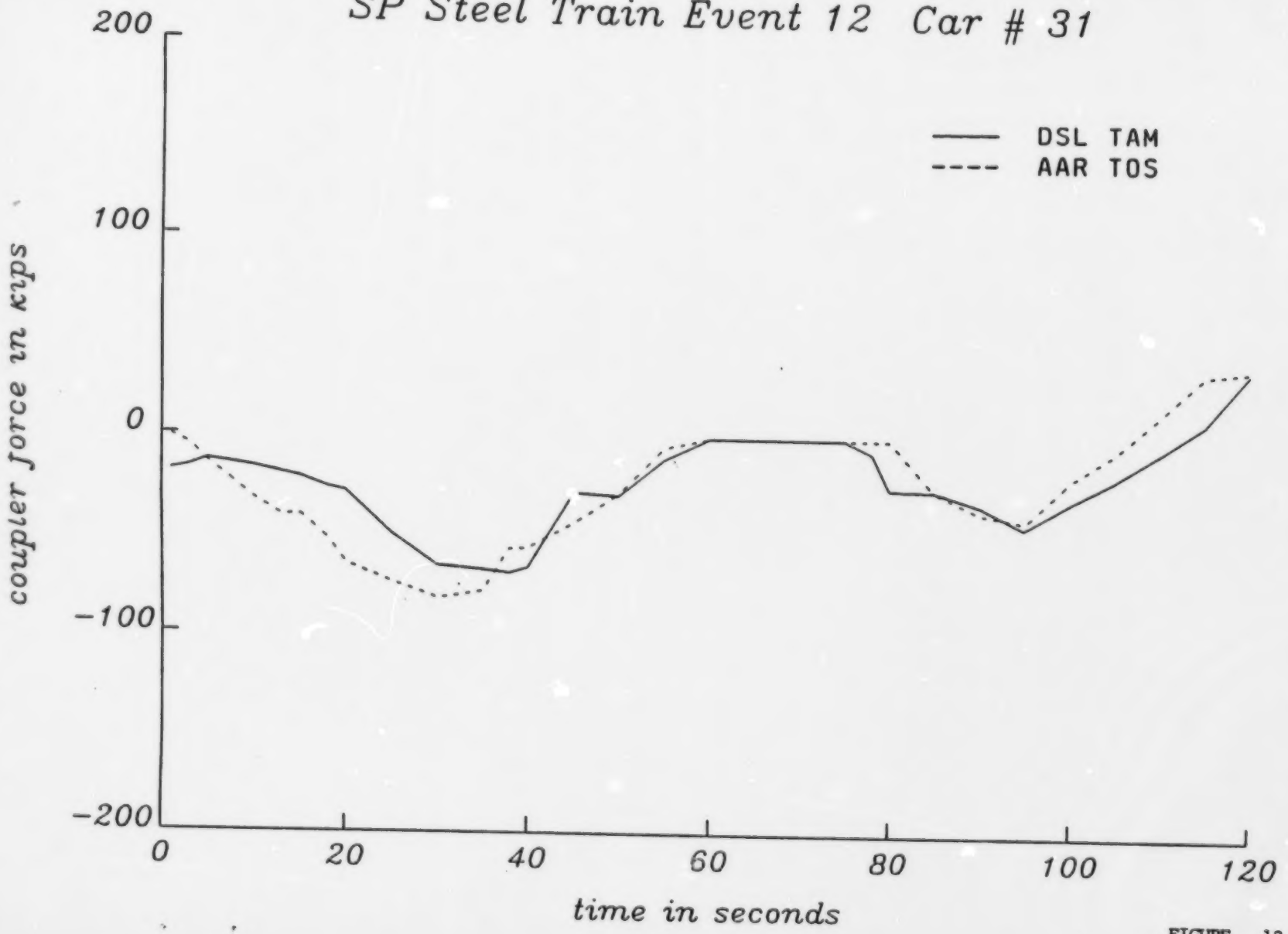

SP Steel Train Event 12 Car # 31
DSL TAM
AAR TOS
coupler force in kips
200
100
0
-100
-200
0
20
40
60
80
100
120
time in seconds

FIGURE 12

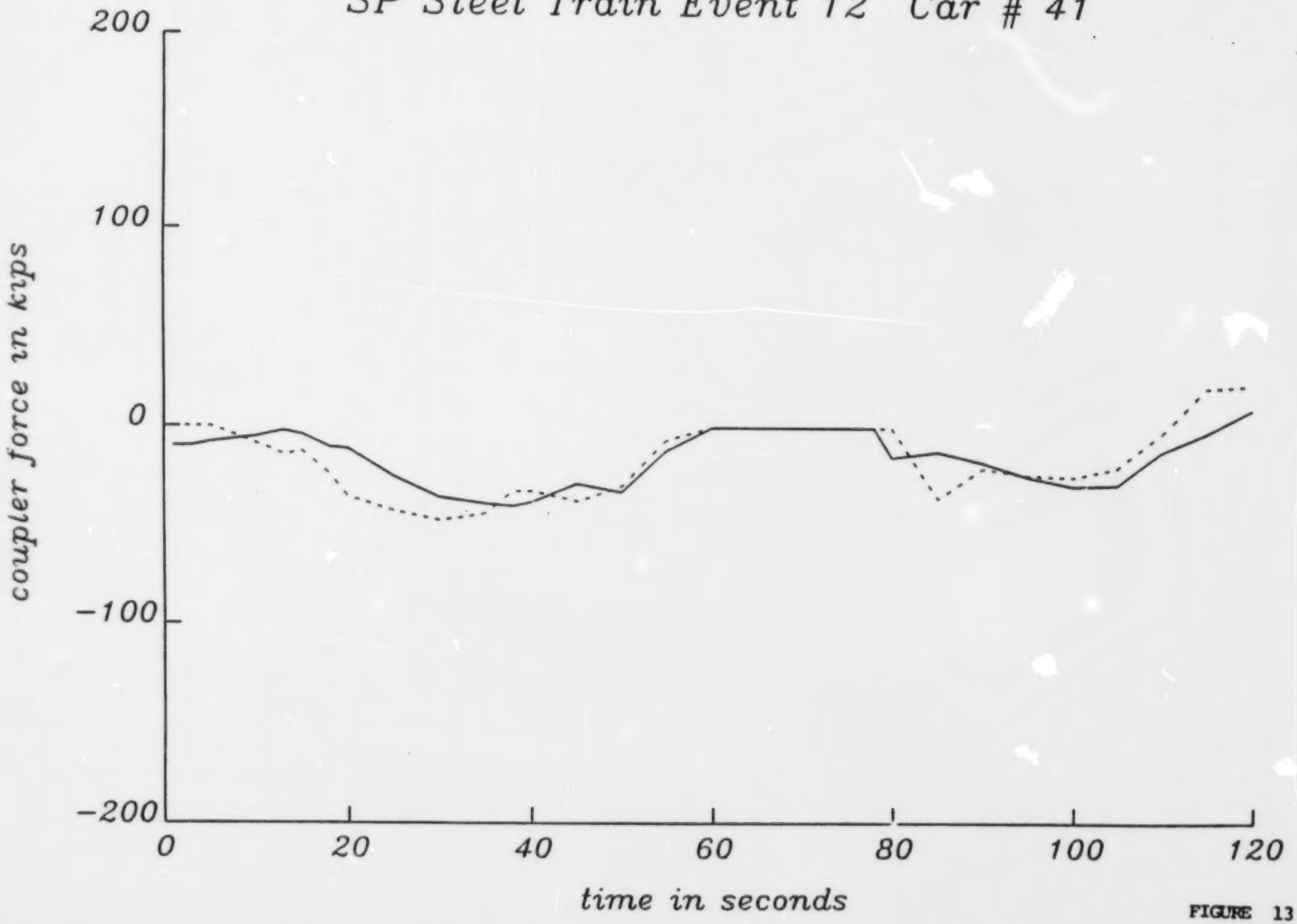

SP Steel Train Event 12 Car # 41
200
100
0
-100
-200
coupler force in kips
0
20
40
60
80
100
120
time in seconds

FIGURE 13

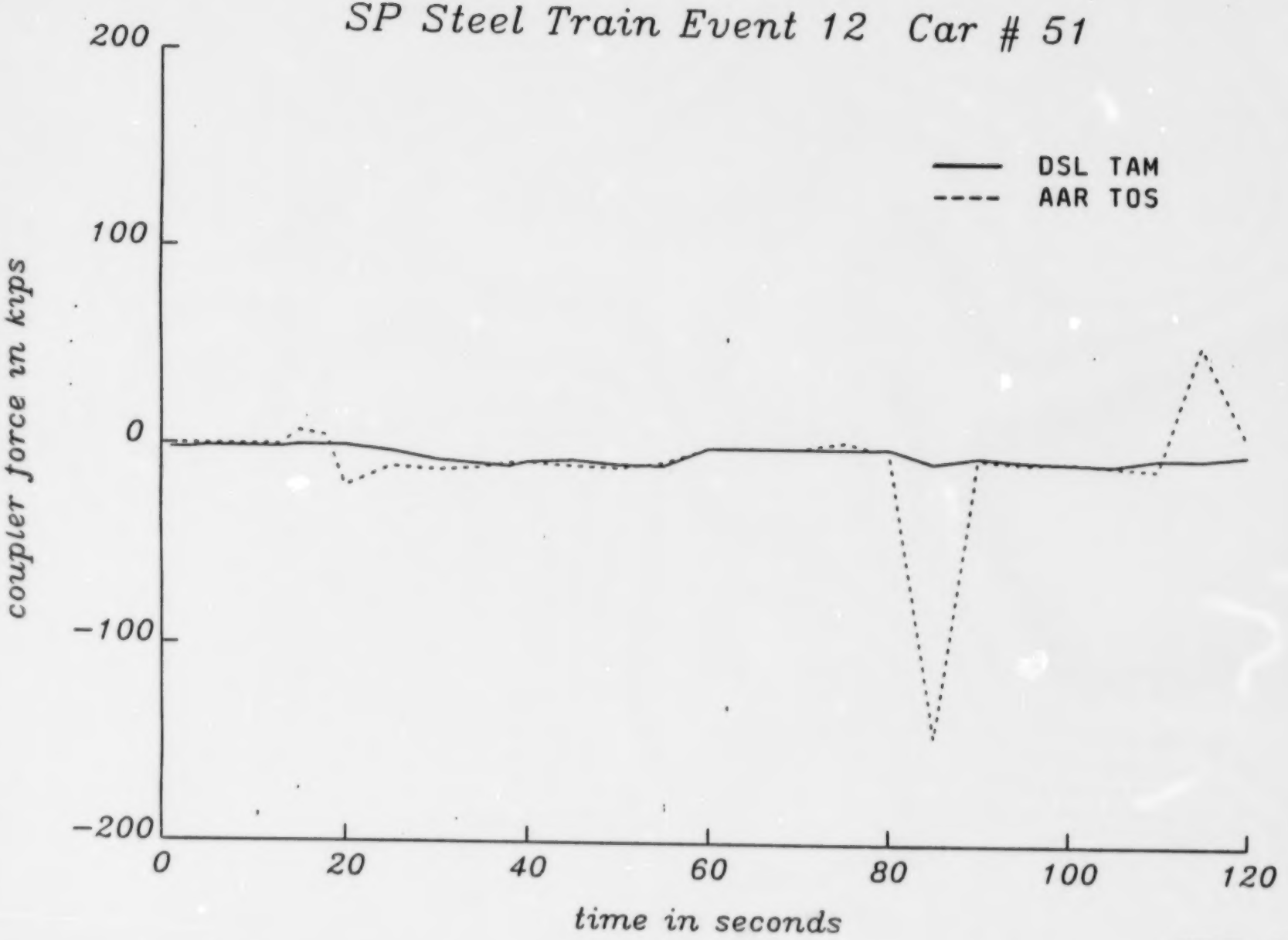

SP Steel Train Event 12 Car # 51
DSL TAM
AAR TOS
coupler force in kips
200
100
0
-100
-200
0
20
40
60
80
100
120
time in seconds

FIGURE 14

APPENDIX

CONSIST OF STEEL COIL TRAIN

TRACK PROFILE FOR STEEL COIL TRAIN EVENT 12

STEEL COIL TRAIN EVENT 12 - COUPLER FORCE CAR 1

CAR 21

CAR 31

CAR 41

CAR 51

CONSIST OF STEEL COIL TRAIN

four (4) locomotives - SD-45T-2; 3600 hp each; 205 tons each

Postion	Car Number	Gross Weight	
car 1	SP 595596	122 tons	** instrumented car**
car 2	SP 595538	128 tons	
car 3	SP 595559	127 tons	
car 4	SP 595548	125 tons	
car 5	SP 595526	122 tons	
car 6	SP 595570	124 tons	
car 7	SP 595503	124 tons	
car 8	SP 595531	120 tons	
car 9	SP 595593	130 tons	
car 10	SP 595612	130 tons	
car 11	SP 595573	124 tons	**instrumented car**
car 12	SP 595563	123 tons	
car 13	SP 595614	124 tons	
car 14	SP 595529	123 tons	
car 15	SP 595622	124 tons	
car 16	SP 595615	130 tons	
car 17	SP 595555	130 tons	
car 18	SP 595519	125 tons	
car 19	SP 595564	120 tons	
car 20	SP 595510	127 tons	
car 21	SP 595568	125 tons	**instrumented car**
car 22	SP 595539	128 tons	
car 23	SP 595572	126 tons	
car 24	SP 595536	127 tons	
car 25	SP 595556	125 tons	
car 26	SP 595578	128 tons	
car 27	SP 595511	120 tons	
car 28	SP 595611	130 tons	
car 29	SP 595605	129 tons	
car 30	SP 595620	124 tons	
car 31	SP 595610	123 tons	**instrumented car**
car 32	SP 595619	124 tons	
car 33	SP 595621	125 tons	
car 34	SP 595582	129 tons	
car 35	SP 595581	130 tons	
car 36	SP 595522	124 tons	
car 37	SP 595565	124 tons	
car 38	SP 595590	124 tons	
car 39	SP 595518	124 tons	
car 40	SP 595534	124 tons	
car 41	SP 595551	120 tons	**instrumented car**
car 42	SP 595547	122 tons	
car 43	SP 595617	127 tons	
car 44	SP 595618	125 tons	
car 45	SP 595583	128 tons	
car 46	SP 595586	124 tons	
car 47	SP 595537	128 tons	
car 48	SP 595549	128 tons	
car 49	SP 595523	127 tons	
car 50	SP 595577	126 tons	

car 51	SP 595516	127 tons	**instrumented car**
car 52	SP 595512	127 tons	
car 53	AAR 100	64 tons	**research car**
car 54	SP 138	66 tons	**sleeping for crew**
car 55	SP 137	69 tons	**kitchen and support**
car 56	SP 1741	26 tons	- caboose -

GROSS WEIGHT OF THE LOAD REVENUE CARS (cars 1 thru 52)
6524 tons

GROSS WEIGHT OF THE LOCOMOTIVES (@205 tons each)
820 tons

GROSS WEIGHT OF THE ENTIRE TRAIN
7569 tons

LENGTH OF THE ENTIRE TRAIN
2959 feet

The entire train had ABD brakes, with the exception of the AAR 100 which had AB.

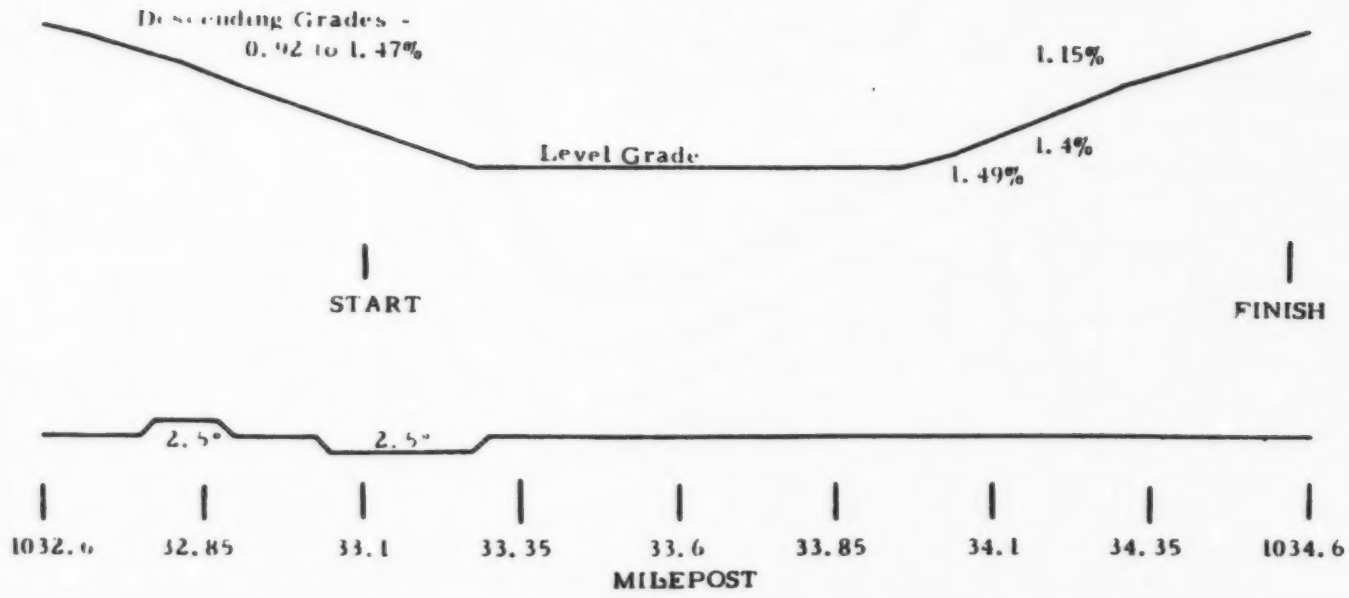


FIGURE 1 - COIL STEEL TRAIN EVENT 12 - TRACK PROFILE

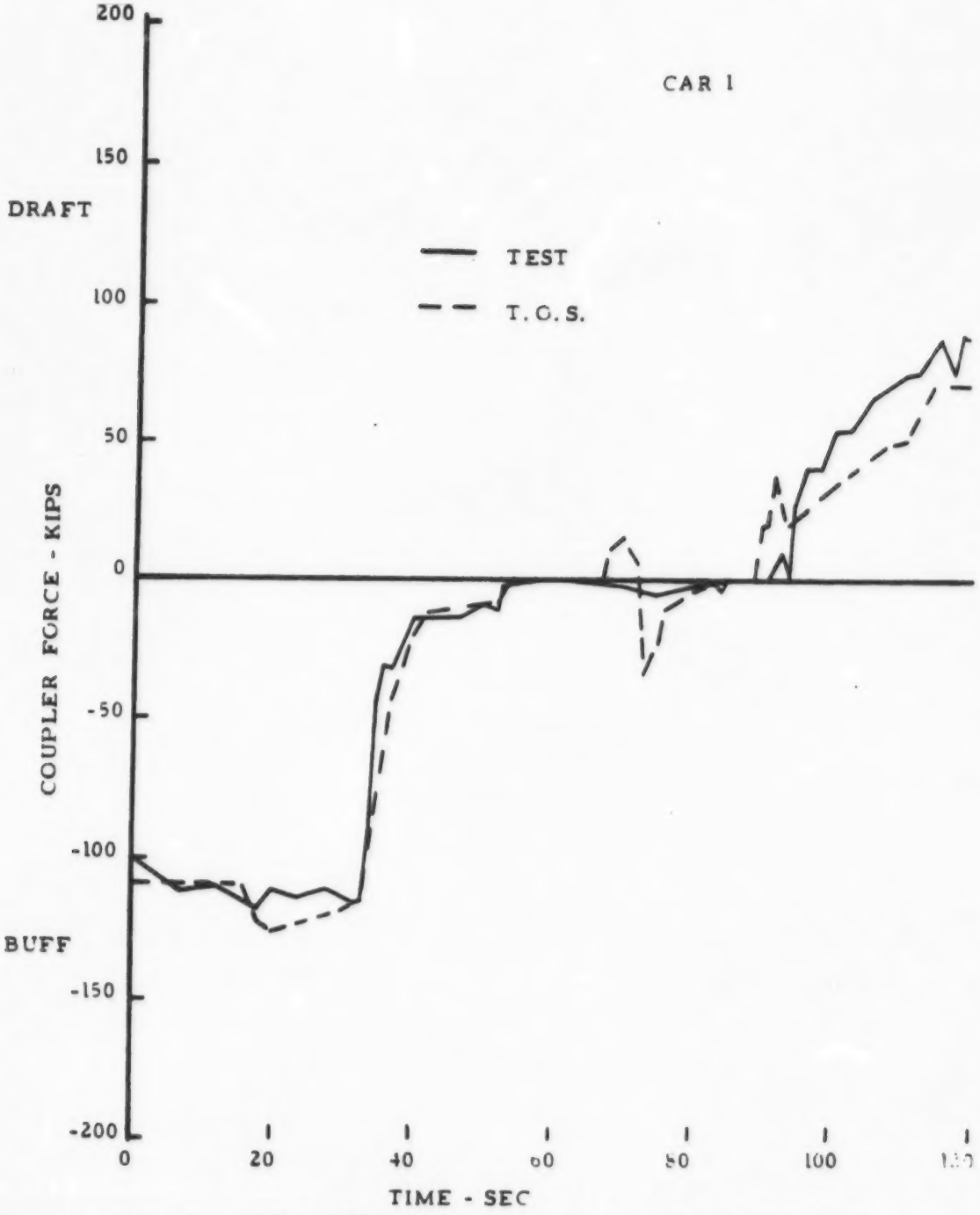


FIGURE 3 - COIL STEEL TRAIN EVENT 12 - COUPLER FORCE

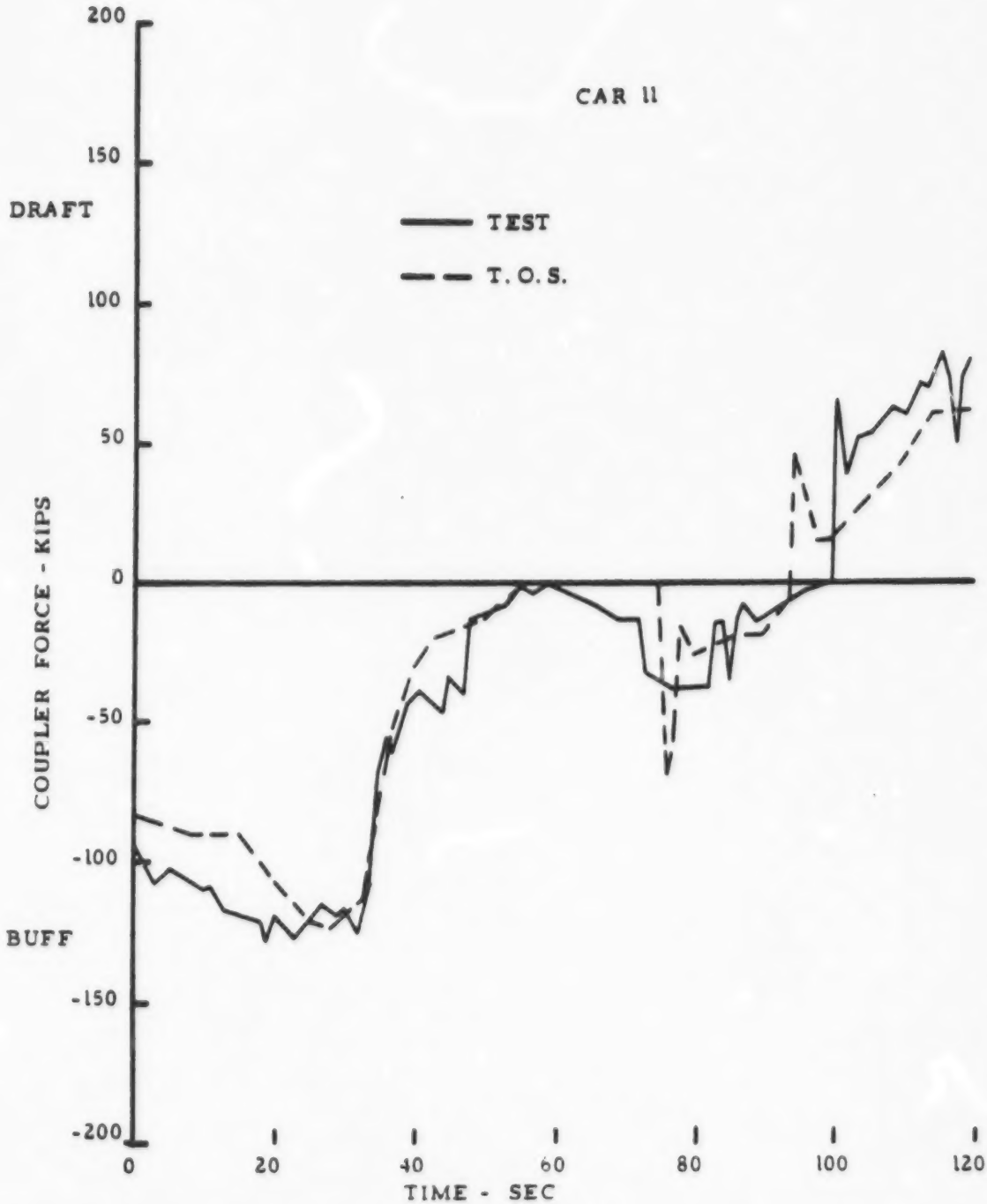


FIGURE 4 - COIL STEEL TRAIN EVENT 12 - COUPLER FORCE

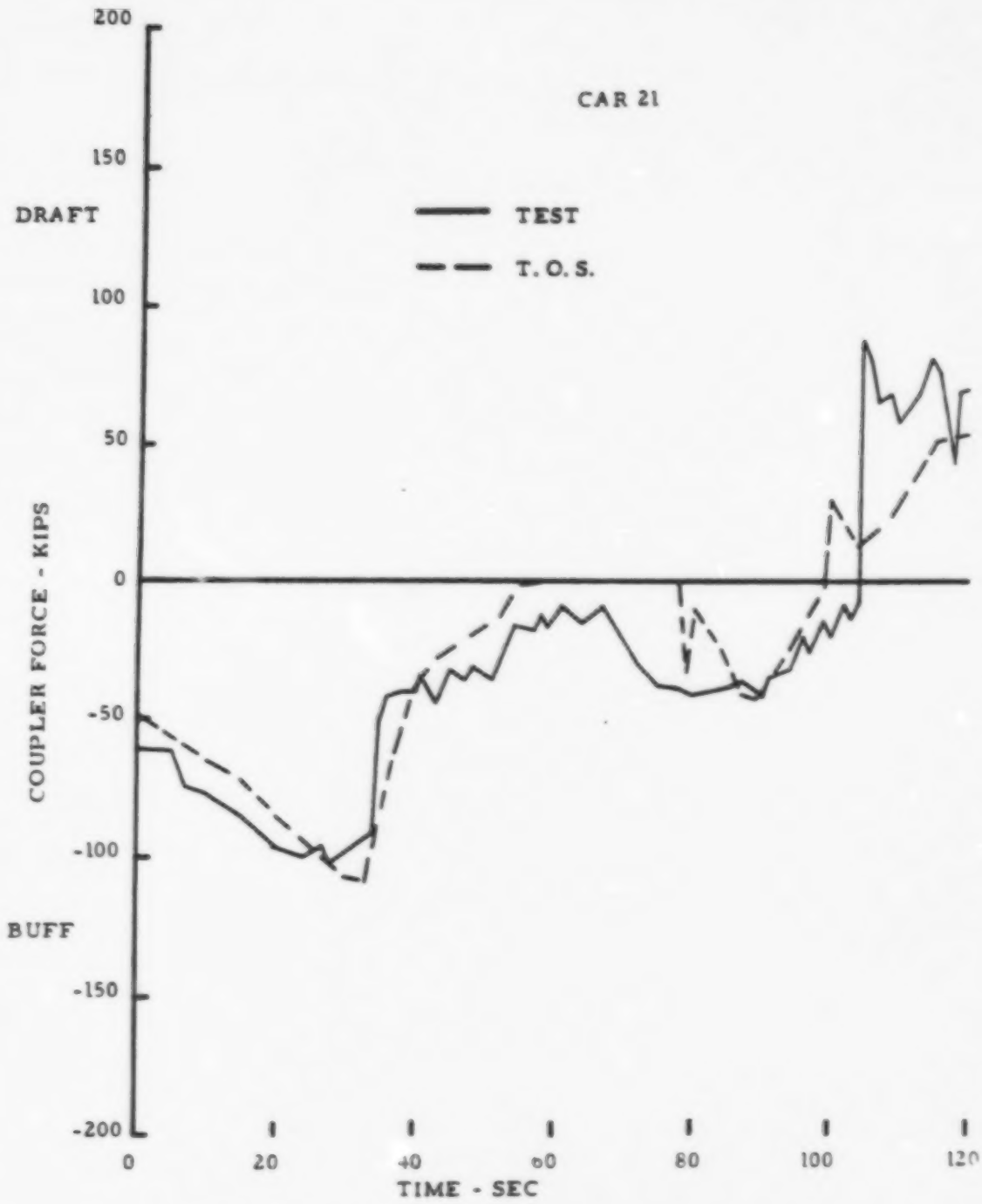


FIGURE 5 - COIL STEEL TRAIN EVENT 12 - COUPLER FORCE

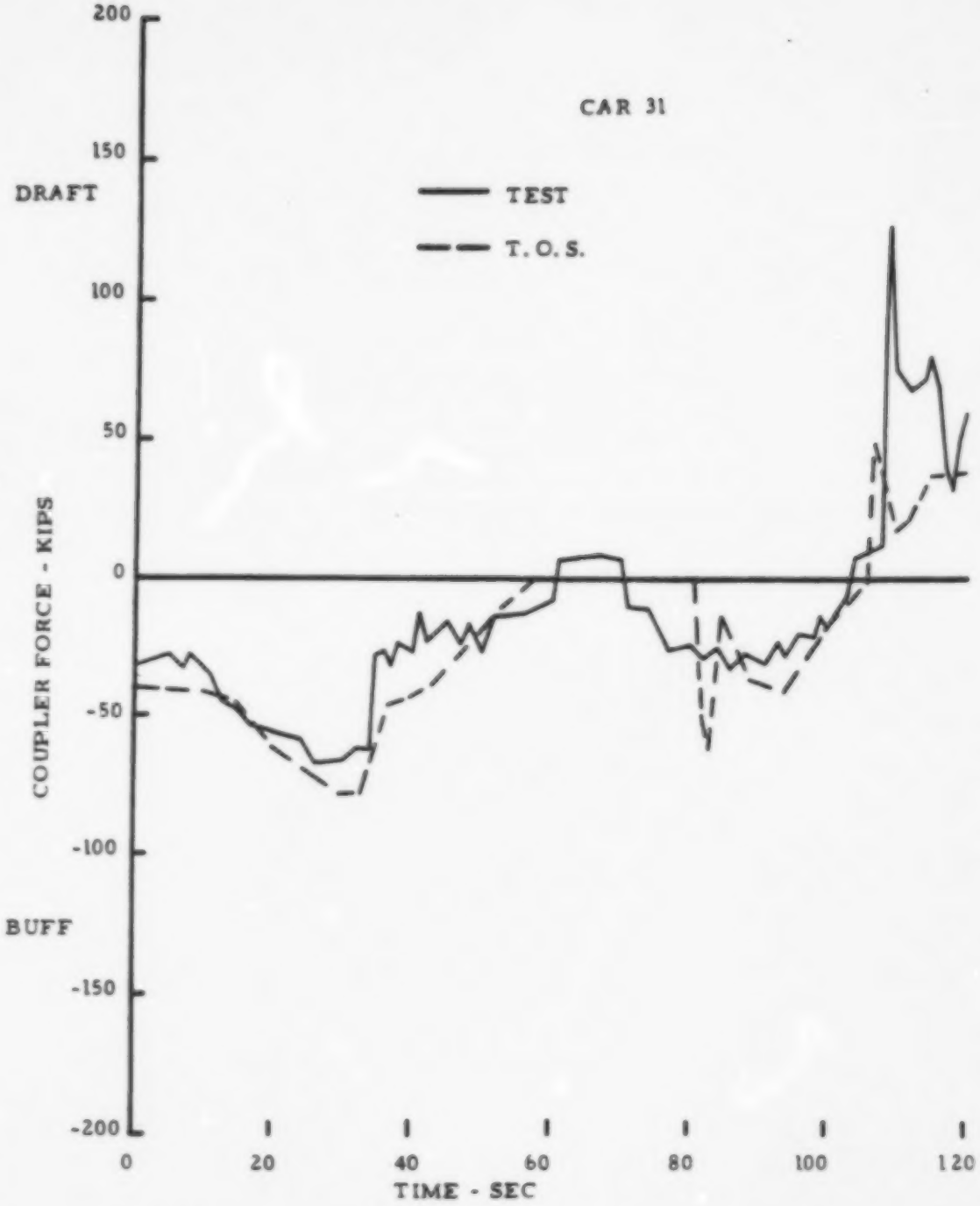


FIGURE 6 - COIL STEEL TRAIN EVENT 12 - COUPLER FORCE

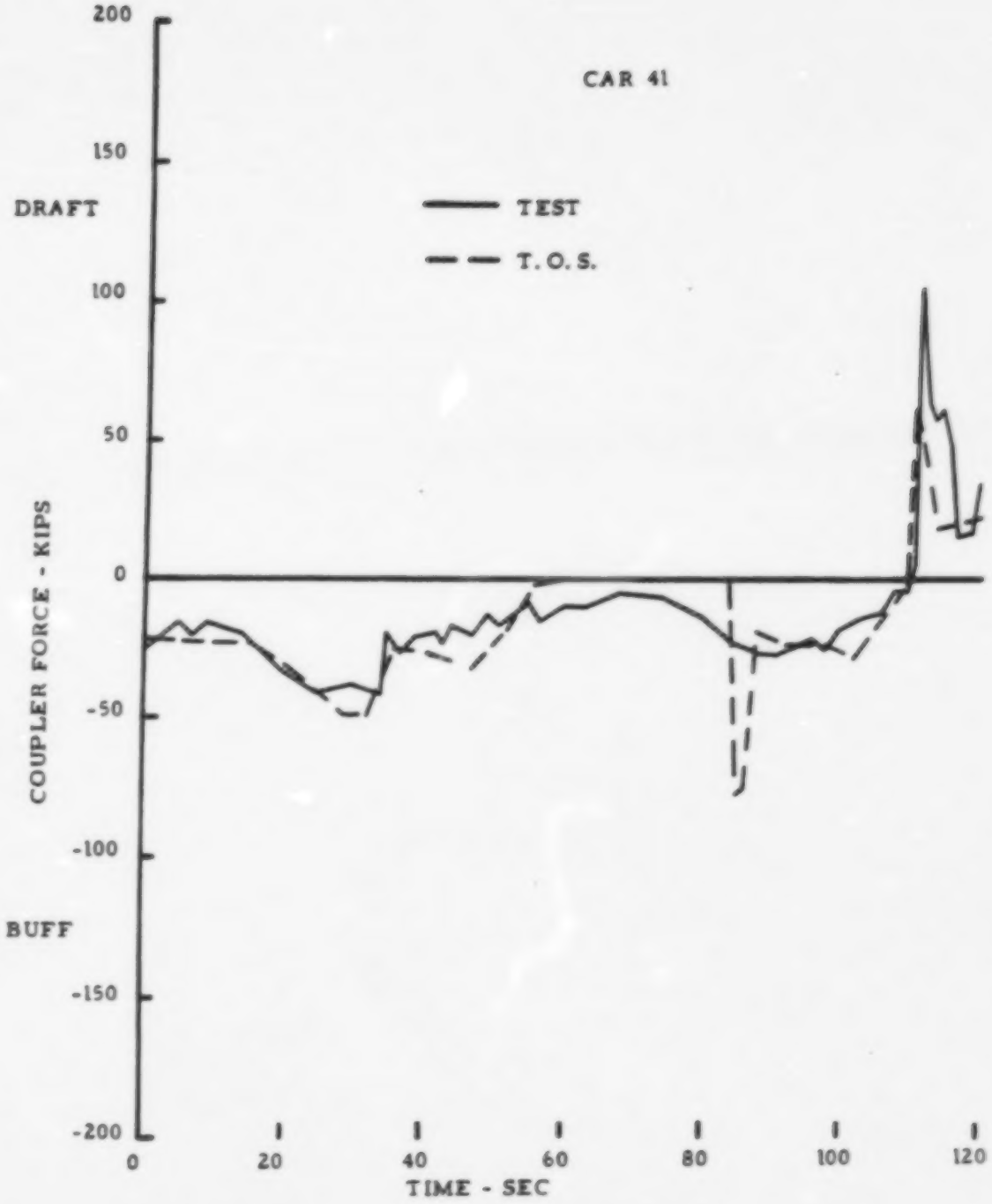


FIGURE 7 - COIL STEEL TRAIN EVENT 12 - COUPLER FORCE

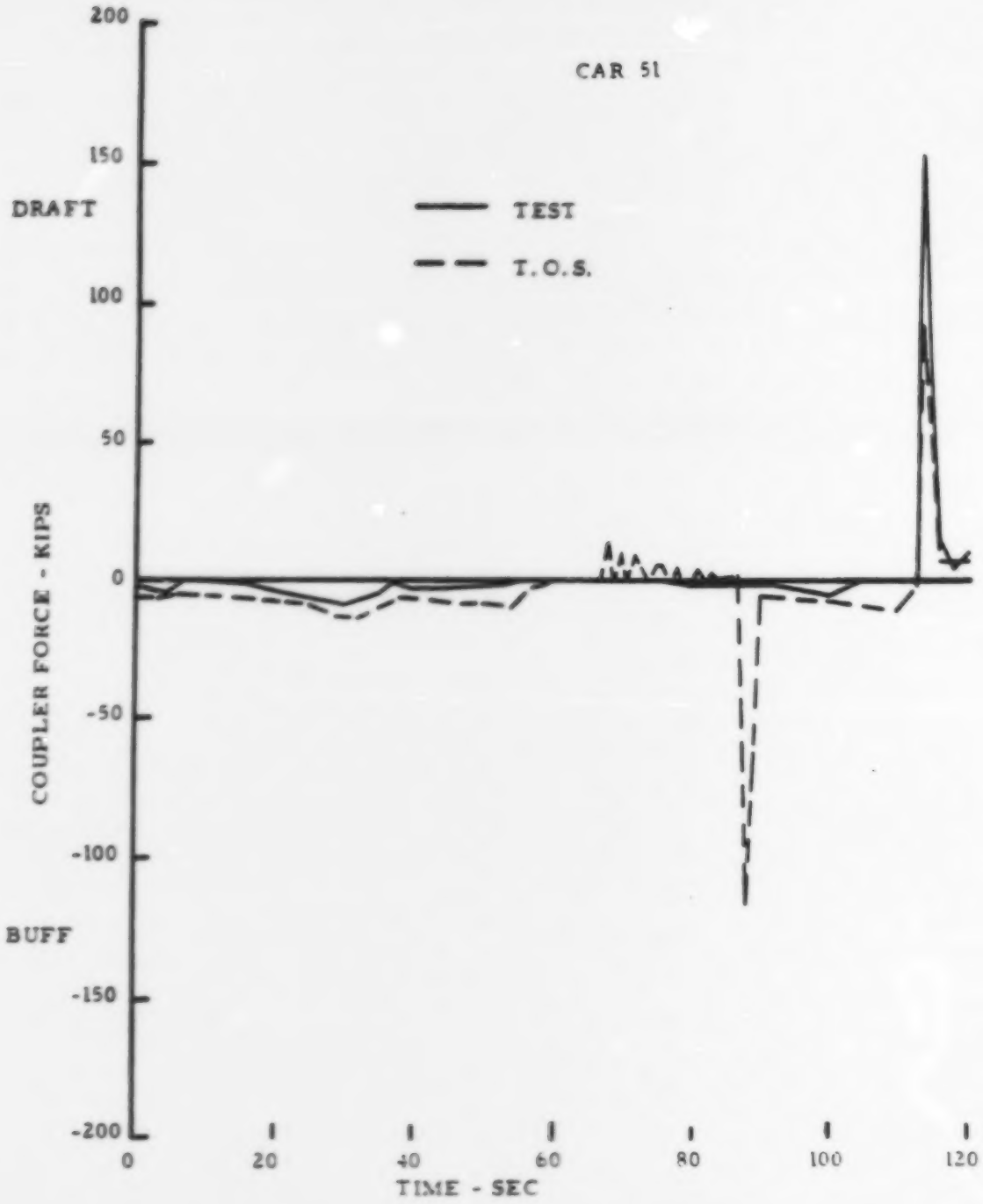


FIGURE 8 - COIL STEEL TRAIN EVENT 12 - COUPLER FORCE

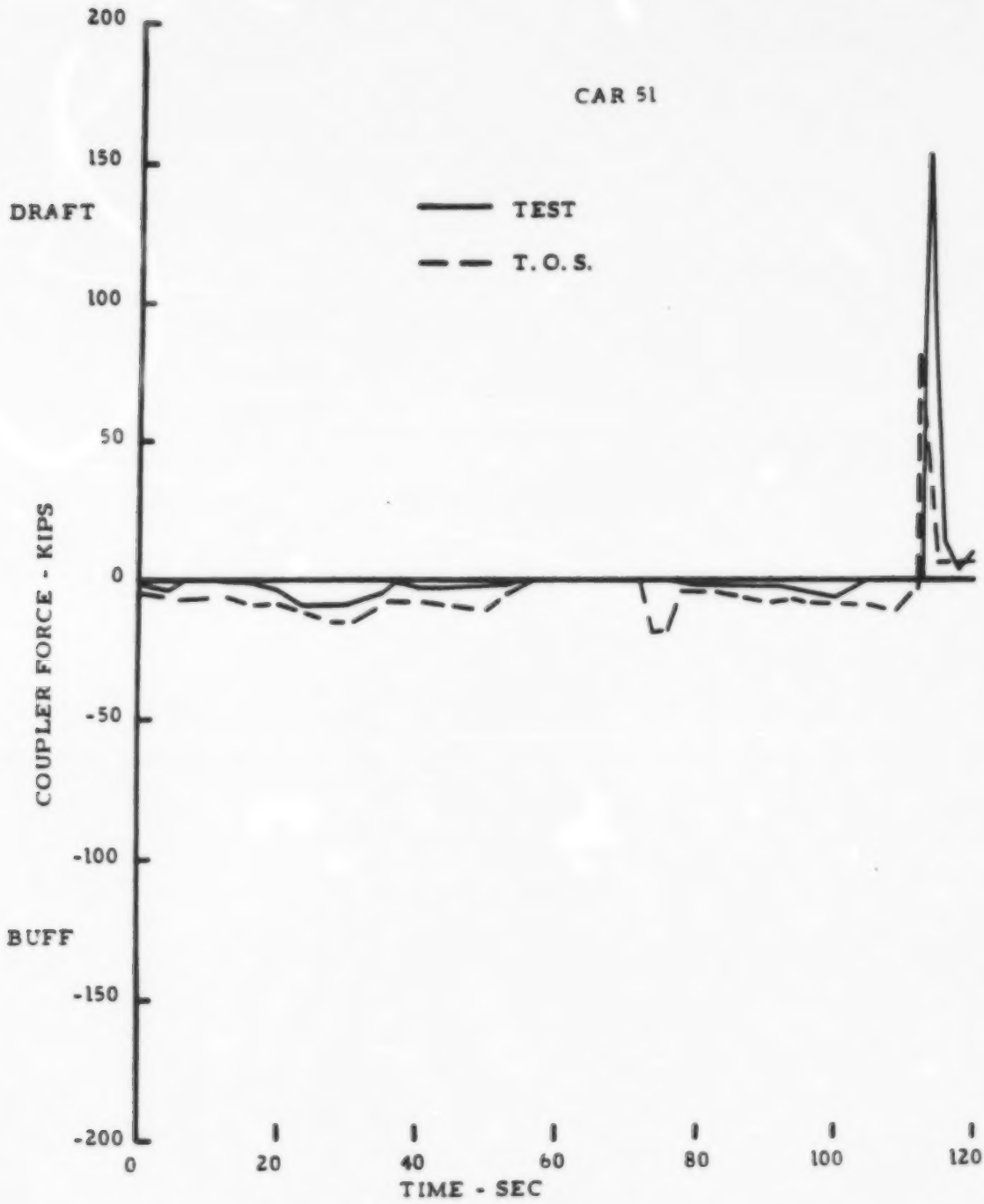


FIGURE 15 - COIL STEEL TRAIN EVENT 12 - COUPLER FORCE
WITH MODIFIED RESISTANCE (DAVIS) FORMULA